British Iron and Steel
AD1800–2000 and Beyond
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Edited by
C. Bodsworth
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PREFACE

Several books have been published which describe the evolution and growth of the British iron and steel industry. Most of these provide accounts of the developments in manufacturing methods that have taken place. Some also discuss the products. Only limited reference is usually made, however, to the reasons why the changes were made or to the progressive evolution of the underlying scientific understanding that has transformed the modern approach to the design and operation of processes and to product development. There is no comprehensive coverage of the vast changes that have transformed the industry during the second half of the twentieth century. The theme for the present treatment was proposed by Professor Jack Nutting (now deceased) who suggested that practitioners who had witnessed many of these changes should record their experiences for the benefit of posterity.

The first chapter sets the scene by outlining the changes which resulted in the vast increase in output during the nineteenth century. It identifies also the initial stages of the transition from the control of operations and the development of new processes based upon trial and error and accumulated experience towards the adoption of a more analytical method based on experimentation and scientific deduction. The following chapter describes the continuation of this trend through an examination of the sequence of changes that have occurred during the last 100 years, with reference to some of the problems encountered and the solutions which were derived. It summarises the stage of development reached by the end of the second Millennium.

Founded in 1869, as described in Chapter 3, the Iron and Steel Institute became the principal vehicle for the communication of information about manufacturing and conceptual developments between people working in the industry. It initiated also collaboration between companies by participation in co-operative research activities. This led to the formation of several Research Associations. Most of these served specific sectors of the industry, such as the cast iron, steel castings and spring manufacturers. The most comprehensive coverage was provided by the British Iron and Steel Research Association and the account of its activities in Chapter 4 draws attention to the important contribution made by these bodies.

As the mature industry moves into the twenty-first century, the fifth chapter speculates on the most probable lines for future development. Each chapter is self-contained. Although this has resulted in some repetition, the chapters can thus be read independently and in any order.

The Appendix presents brief histories of some of the leading companies that made major contributions to the development and growth of the industry during the nineteenth and twentieth centuries, but whose names are now consigned to history. The profiles are reproduced from an on-going series of reports which are being published in the journal *Ironmaking and Steelmaking*.

I place on record my appreciation of the efforts of the co-authors who have contributed chapters to the book and without whose support the preparation of this publication would not have been completed. Thanks are recorded also to the many
people who have written and/or have contributed to the accounts of the histories of the individual companies described in the Appendix.

Since this back was written, British Steel Corporation and Hoogovens in Holland have merged and have since formed the Corus Group.

Colin Bodsworth
December 1999.
CHAPTER 1

Nineteenth Century Developments

C. BODSWORTH

1. INTRODUCTION

The British iron and steel industry achieved phenomenal growth during the nineteenth century, but there were several periods of boom and depression and the rate of change varied markedly, both from one category of products to another and from one decade to the next. Thus, the annual production of pig iron doubled during the first decade, stimulated by the demand arising from the Napoleonic wars. The industry then contracted during the recession that followed the restoration of peace, and higher annual outputs were not achieved until another twelve years had elapsed. Compared with the performance in 1800, the production of pig iron had increased by over twelve fold by 1850 and by roughly fifty fold at the end of the century. This growth was aided by an almost zero cumulative rate of inflation from the end of the Napoleonic wars to the end of the century. In marked contrast, wrought iron production increased by only about nine fold during the first half of the century, reached a peak in 1882 and showed a slow annual decline thereafter. There appears to be no reliable estimates for steel production in the early nineteenth century, but the output increased by about 100 fold during the last four decades with the development of the Bessemer and Siemens bulk steelmaking processes. Several factors contributed to bring about these spectacular rates of change, which have not been approached in subsequent years.

The population of Britain was about 11 million in 1800 but it was increasing more rapidly than the average rate of growth during the previous century and had risen to 22 million by the time of the first census in 1851. Agriculture had traditionally been the major employer, but the development of wind and water power had reduced the labour requirements and this trend was accelerated when steam powered mechanical equipment was introduced. The industry could no longer provide sufficient work for the rapidly expanding labour force and increasing numbers of people were available for employment in other occupations.

Machinery and machine tools were still very expensive in 1800. The water wheel was still the major source of motive power and the industrial revolution had made only slow progress. The applications of steam power began to expand rapidly in the first decade, following the expiry of the Bolton and Watt patent for the condensing steam engine. The power that could be obtained from an engine was also
increased considerably by using the more accurately bored cylinders that were now being produced using Wilkinson's cylinder boring technique. The 'dark satanic mills' started to disfigure the agrarian landscape as factories began to displace home workshops and provide employment for the more numerous urban workforce. The first fully mechanised production line was a set of forty-four machines, which were designed by Mark Isambard Brunel and built by Henry Maudsley to make the wooden blocks required for the rigging of sailing ships. The machines were installed at Portsmouth dockyard in 1809 and some of these are still on display in a local museum.

The number of works engaged in the production of cast and wrought iron increased significantly to meet the growth in demand. A few companies began to integrate production from ore mining through to the production of semi-finished wrought iron products, but most continued as either pig iron or wrought iron manufacturers. This division of activities continued throughout the century. The majority of works began life as a small family business, which was usually located on one site. As larger works began to develop from the midcentury onwards there was a fairly rapid demise of many of the smaller companies. Even the larger works, however, were usually owned by one or two individuals and this practice continued in many cases after the introduction of the limited company status which facilitated the raising of finance for expansion. The processes of amalgamation and acquisition of competitor companies did not really make progress before the beginning of the twentieth century.

A major new demand for ferrous metals arose from developments in transportation. Carriage of materials to and from the works was aided by the development of the canal system, but the canals used only relatively small quantities of iron. Road transport also created little demand until towards the close of the century. Richard Trevithick designed a steam tractor to haul a passenger coach, which underwent road trials at Cambourne in 1801, but it was not a success. A similar fate befell a patent in 1825 for a caterpillar-tracked vehicle. George Seldon's patent, which led to the building of the first effective road locomotives, was not issued until 1879 and the first Daimler patent for a petrol engine was published in 1885. Horse-drawn transport remained dominant on the roads for most of the century.

Shipbuilding became a major consumer of iron during the second half century after a relatively slow beginning. The first regular passenger-carrying steamboat service, sailing between Glasgow and Greenock, was provided by a wooden hulled paddle ship named the *Comet*, launched in 1812. Over twenty steam powered ships were in use in Britain by the end of that decade. The first iron-hulled steam ship, the *Aaron Manley*, was launched on the Thames in 1820. An iron-hulled sailing ship crossed the Atlantic in 1838 and in 1845 I. K. Brunel's *S.S. Great Britain* was the first steam-powered, iron-hulled passenger ship to cross the Atlantic, but steam power and wrought iron hulls only slowly replaced the traditional wooden sailing ships. The British Navy was particularly slow to adopt the use of new materials. The first iron warship, *H.M.S. Dover*, was launched in 1842, but by 1870 the Navy was operating only 130,000 tons of wrought iron shipping, compared with 368,000 tons of
The major transport demand for ferrous materials came from the development of the railways. Richard Trevithick’s steam locomotive Catch-me-who-can was exhibited in 1808 when it ran on a small circular rail track at the Orange Tree public house at St Pancras in London, but the demonstrations ended when the track sank into soft earth and the locomotive toppled over. The Puffing Billy locomotive was built in 1813 for use in a Durham colliery and Stephenson built his first locomotive for a colliery in the following year. Nine years later, the Stockton to Darlington railway was opened in 1825 as the first passenger carrying line. Five years later, the Manchester to Liverpool line was opened. The pace then accelerated rapidly, with 1952 miles of track completed by 1843 and 17,000 miles of track were in use by 1878. All the early tracks were laid with rails made from cast or wrought iron, which were the only suitable materials then available. Trials in 1862, however, using a section of Bessemer steel rail at Chalk Farm on the line into Euston station gave a twenty fold increase in the rail life. This led to an enormous demand for steel rails and, for a time, about 70% of Bessemer steel production was used for this purpose.

A large demand arose also from developments in civil engineering. The traditional buildings constructed in brick or stone were too expensive to erect for use as factory buildings and they provided inadequate floor space for the installation of large items of machinery. Cast iron beams and girders with cast or wrought iron floor plates were required for the construction of ‘fireproof’ mills. The Crystal Palace, which was erected in glass and cast iron to house the 1851 exhibition, clearly demonstrated the greater flexibility in design that was obtained by the use of iron and boosted the constructional applications. Following the success of Darby’s iron bridge at Coalbrookdale, cast iron bridges were built across the river Wye at Chepstow in 1814 and at Southwark in London in the following year. The high level bridge at Newcastle was completed in 1848. Telford built the first suspension bridge in 1826 to span the Menai Straights. Stephenson’s Britannia tubular railway bridge, constructed in 1850 by the side of the suspension bridge, and Brunel’s Royal Albert bridge at Saltash, completed in 1859, were two outstanding examples of the many iron bridges that were built for the new railways. The first steel bridge was erected across the Firth of Forth in 1890. The numerous wars which were fought between nations in Europe and in Africa in the second half of the nineteenth century resulted in both a major growth in the use of iron and steel for armaments and a subsequent demand for materials to repair the ravages of war when peace was restored.

The total production of ferrous materials in Britain in 1800 was not significantly different to the outputs from a number of other European countries, but the rate of industrial development was more rapid in Britain than in any other country.
other nations started to emulate the British development of the railways, they lacked a domestic supply of rails and rolling stock. A flourishing export trade for British products ensued and this led to a more rapid growth of the ferrous industries in Britain than would otherwise have been required to satisfy the home market. In 1806 Britain produced one third of the total amount of pig iron made in the world. Fifty years later the output had increased to equal 50% of the total world production and in 1869 the production of pig iron in Britain was greater than the total output from Germany, France and Belgium. This dominant position was further strengthened by the development here of the Bessemer and Siemens steelmaking processes. But the British dominance did not last for many years as other countries also began to develop iron and steel production. By 1885, using mainly the acid Bessemer process and with the imposition of import tariffs to stimulate the domestic industry, the USA had become the largest steelmaking country in the world. Germany moved up into second place in the mid 1890s as the development of the basic steelmaking processes allowed exploitation of the European phosphoric iron ores.

The growth in production as the century progressed was accompanied by the birth and the early development of scientific methods for process control. The traditional modes of operation, based on practical experience and 'rule of thumb', gradually succumbed to a more logical approach as technological investigations began to identify the factors which influenced the manufacturing processes and the manner in which those factors could be controlled to improve the quality and productivity. The consistency and the quality of the products improved rapidly during the last two decades following the development of fairly reliable methods for chemical analysis and then with the introduction of metallographic examination. The range of mechanical properties that could be attained in the ferrous products was increased also by the production of the first commercial grades of alloy steels.

Frequently during the century inventive geniuses conceived new processes, such as electric steelmaking, direct reduction of iron ores and thin strip casting, which were too far in advance of the scientific understanding or the engineering capabilities of the time. Consequently, they were shelved as impractical concepts and remained dormant until they were reinvented and developed into viable processes during the twentieth century. When compared with the standards that have been achieved today, the ferrous industries were still rather primitive at the end of the period under review. But the progress that had been made, particularly during the last half of the century, in the scale and efficiency of production and in the range and quality of the products, was a very significant achievement.

2. IRONMAKING PROCESSES

2.1 Blast Furnace Practice

2.1.1 Furnace Design and Production
The design, construction and operation of a blast furnace changed very significantly during the nineteenth century. The squat brick structure with a square or
conical external cross-section strengthened with wrought iron tie bars, which had evolved during the previous century, continued as the dominant form for the first few decades, but the hand-moulded fireclay lining gradually gave way to a firebrick construction. There was a progressive change to the use of bricks with a higher alumina content in the hearth, the bosh and sometimes in the lower stack, to improve the refractoriness and reduce the rate of fluxing of the brickwork. By the 1860s the external shape had developed into a free standing cylindrical form with the stack clad in boiler plate and resting on a cast iron ring which was supported on cast iron columns. Furnaces erected in the 1880s and 1890s were not markedly different in external appearance to many that were in use half a century later. The average annual output from a furnace increased from about 1100 tons in 1800 to 9000 tons in 1870 and then rose more rapidly to 23,000 tons in 1899.

The maximum height of a charcoal blast furnace was restricted to about 6 m by the low crushing strength of the charcoal, but this limitation was removed when coke was used for smelting. When Abraham Darby introduced the use of coke, the total cost of operation was higher than with charcoal. Consequently the majority of blast furnace operators continued to use charcoal until, as experience accumulated, the relative costs of the two modes of operation were reversed. Most furnaces were coke charged by 1800, but they were still built to the designs that had evolved for charcoal operation; some continued to use charcoal. Eleven charcoal furnaces were still in use in 1806 and produced just over 3% of the total pig iron output. The last English charcoal furnace was blown-out in 1829, but a small furnace at Bainawe, near Loch Awe in Argyllshire, was still in operation in 1885, smelting Cumberland hematite ore with locally produced charcoal.

Only a relatively low blast pressure could be obtained using bellows driven by a water wheel and this also imposed a limitation on the height of a furnace. The restriction was not removed when Newcomen engines were first used in an iron works, for the engine was usually employed only to return the water from the wheel sluice to the storage dam in periods of low rainfall and so allow year-round operation of the furnace. John Wilkinson had used a direct drive from a steam engine to the bellows at the Brosley works in 1776, but steam powered blowing engines were not widely employed until towards the end of the first decade of the nineteenth century. Thereafter furnace height increased rapidly to 12–15 m and the volume rose from about 42 to 170 m³. A few furnaces in Wales had attained a height of 18 m by 1820.

John Gibbins introduced the first significant change in the cross-section of the furnace in the late 1830s. From observations of the internal shape of furnaces which had been blown out for relining, he recognised that during use, the initial square cross-section was gradually eroded into a cylindrical form. A new furnace was built accordingly with a cylindrical hearth and stack and it was found that the productivity was increased by a third when compared with furnaces of the traditional design.

During the 1830s, the upper shaft was almost doubled in width, relative to the diameter of the hearth. This reduced the gas velocity and allowed more time for
heat transfer from the gas to the charge, resulting in a lower top gas temperature. Steam powered lifts were now widely used to raise the barrows containing the charge materials to the platform at the top of the furnace. The stack was still supported on a massive masonry construction that traditionally incorporated four arches (Fig. 1). One of these contained an open fore hearth which was partially blocked by a dam wall to prevent a continuous discharge of molten metal from the furnace. The other arches provided access for the installation of the tuyeres, which had increased in number from a single unit when the bellows were driven by a water wheel to two or three when larger blast volumes became available using steam driven blowing engines. The greater ease of access to the hearth when the stack was supported on cast iron pillars allowed more tuyeres to be inserted to give a more uniform distribution of the blast and the number gradually increased to a maximum of eight. The open fore hearth was also replaced by a tap hole, allowing the furnace to be operated at higher blast pressure. This made possible a further increase in the height of the furnace. By the 1870s several furnaces about 25 m high had been built with volumes ranging from 50 to 700 m³. A few were built with a

Fig. 1 Early nineteenth century blast furnaces (J. Iron Steel Inst. 1893, (2) Plate XXXI).
height of about 31 m and volumes of 850 to 1200 m$^3$, but opinion generally seemed to indicate that this exceeded the optimum size. The majority of furnaces in operation at the end of the century had an internal volume of at least 560 m$^3$. The early furnaces built in a round form were strengthened with wrought iron bands fixed round the stack. These proved inadequate to withstand the pressures and to prevent the brickwork from bursting in the larger furnaces so, from midcentury onwards, the practice gradually developed of enclosing the stack within a shell of wrought iron plates.

There was no consensus concerning the optimum taper for the stack. Initially the maximum internal diameter was at the midsection and it tapered inwards both to

the top of the bosh and to the throat. This shape gradually gave way to a more cylindrical form. Some furnaces tapered inwards gently from the top of the bosh to the open top, while others had an almost parallel stack and tapered in sharply at the throat (Fig. 2), but it was eventually recognised that the tendency for scaffold formation was decreased as the walls of the bosh became steeper. The angle was increased further after scale model studies with a glass-fronted construction simulating a slice along the vertical axis of a furnace revealed a zone of stagnant charge located at the junction of the bosh with the stack when the bosh angle was too low.

Preparation of the burden materials advanced only slowly during the century. During the early decades, the ore was charged in the 'as mined' condition, or after calcining to remove carbon dioxide and water from the clay-band ores. The larger pieces were usually broken up with a sledge hammer, solely for convenience in filling the charging barrows. As the years passed it was recognised that the furnace worked more smoothly with a uniform sized burden and the larger works installed crushers to size the ore. With open top operation, most of the fines in the burden were blown out from the furnace into the atmosphere. They blocked the gas exit when closed top operation was introduced, so the fines were then screened out from the burden. Some attempts were made to produce pellets or briquettes from the fines, but generally, no satisfactory methods of agglomeration had been developed by the end of the century. The fines were simply rejected as backfill at the mines. As recognition of the conditions inside the furnace slowly advanced in the second half of the century, some works began to blend ore supplies from two or more sources to improve the furnace performance and productivity.

Table 1 gives the output of pig iron and, where data are available, the total number of furnaces and the average number in blast for each year of the century. Reliable estimates for production are only available from midcentury and there is often marked variation between different estimates for output in earlier years. It is evident, however, that national and international events influenced markedly the rate of growth of the industry. As indicated earlier, the output grew rapidly during the Napoleonic wars and was doubled in the decade from 1796 to 1806. Growth continued to reach a peak in 1814, but output then contracted and did not fully recover before 1823. This was reflected in the selling price for pig iron, which fell by nearly 40% during the post war recession. The prices varied with the quality of the iron and the location where it was sold, but an indication of the trends is shown by the data given in Table 2. A high demand in 1825 pushed the price up to £10 per ton. This was the highest return attained during the century, but a rapid rise in output during the next few years was accompanied by a corresponding fall in the selling price.

Output contracted during the recession that occurred in 1841 and 1842, and this was accompanied by a fall in price to under £3 per ton. But a surge in demand during the period of 'railway mania' in the mid 1840s pushed both production and prices to higher levels. An even larger increase occurred in the 1850s at the time of the Crimean war. The boom years of 1871 and 1872 were followed by a deep depression, which reached a low point in 1874 but continued for most of the
Table 1  Number of furnaces and annual production from British blast furnaces: sources Refs. 2, 8–10 and Statistics – United Kingdom: J. Iron Steel Inst., 1869–1900.

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decade. Further periods of boom and depression occurred fairly frequently during the 1880s and 1890s. Apart from a few short peaks, however, the price of pig iron had shown a steady downward trend throughout the century. This can be attributed partly to the marked increase in both the efficiency of operation and the annual production from each furnace in blast and partly to the almost zero rate of inflation which prevailed throughout the century.

Another contributory factor was the occurrence of frequent periods of overcapacity in the second half of the century, as revealed by the variations from year to year in the proportion of furnaces that were in blast. On average, up to a quarter of the furnaces would be off-line at any time for relining and this accounts for most of the furnaces that were not in use during the first half of the century. In later years, the proportion in blast was often much smaller and occasionally, as in 1884 and 1885, it fell below half the total number of furnaces available. Price increases during the 1890s were restrained also by an increasing volume of imports from the developing industries in America and Europe, whilst British exports to those countries were declining owing to the imposition of protective tariffs.

2.1.2 Energy Efficiency
Fuel was a major factor in the cost of blast furnace operation in the early years of the nineteenth century. Although the consumption of coal per ton of pig iron had decreased from the 9 or 10 tons which was normally required at the end of the eighteenth century, the average requirement over the three decades up to 1830 was still about 7 tons. The thermal efficiency was only about 5%. The general consensus at that time was that the blast furnace operated more smoothly and efficiently with
the cold dry air which was prevalent in the winter months than with the air of higher humidity that was normally dominant during the summer. Ice was used at some works to cool the blast and remove part of the moisture by condensation before blowing it into the furnace.

James Beaumont Neilson, the manager of a gas works located near Glasgow, adopted a different approach. In collaboration with Colin Dunlop, Charles Macintosh and John Wilson from the Clyde Iron Works, experiments were conducted at the works using a preheated blast to assist combustion within the furnace. Neilson’s first patent (British Patent. 5701, 1828) described how the blast could be heated to a maximum temperature of 120°C by passage through a cast iron pipe which was heated externally by a coal fire. The initial results were encouraging and a furnace at Clyde Iron Works was changed to continuous hot blast operation in 1830. With a cold air blast the furnace had consumed 8.05 tons of coal equivalent per ton of pig iron. When the blast was heated to 120°C the coal consumption fell to 5.20 tons and this included the 0.4 tons of coal burned in the stoves to heat the air blast. Part of this saving arose from a reduction in the slag volume, for less fluxes were required to combine with the smaller quantity of coke ash contained in the charge.

Neilson devised numerous modifications of the stoves and eventually obtained hot blast temperatures of 300-350°C. The hotter blast raised the flame temperature in the tuyere zone of the furnace, resulting in more rapid melting with smoother operation and the fusion zone moved to a lower position in the furnace. Major problems were encountered in operation, however, mainly as a result of the differential expansion and cracking of the welded joints in the heat exchangers. Many years elapsed before a reliable design was evolved for the higher temperature stoves.

The development of the hot blast practice was particularly opportune for the Scottish iron industry. This region lacked suitable local supplies of both iron ore and coal and had been largely bypassed during the expansion of the iron industry elsewhere in Britain. The Scottish splint coal had a relatively low carbon content and was not suitable for coke making. One of the principle reasons for using coke instead of coal in the blast furnace was the ability to remove most of the sulphur from the coal during the coking operation. The higher flame temperature at tuyere level, obtained with a hot air blast, allowed a more basic slag to be formed in the furnace with a higher sulphur capacity. It was then found that a pig iron with a sulphur content within acceptable limits could still be produced when raw splint coal was substituted for coke in the furnace burden. The practice was first adopted in 1831 at the Calder Ironworks. The fuel consumption fell to 2.25 tons of coal per ton of pig iron when coke was completely replaced by coal.11

David Mushet identified Scottish deposits of black band (carboniferous) ironstone in 1801, which had an iron content of over 60% after roasting. The ore was almost self-fluxing, but it was very difficult to smelt it with a cold blast and only the Calder and the Clyde Iron Works were exploiting the deposits before Neilson’s invention. The higher temperature, which could be attained in a furnace using a hot
blasts, was sufficient to remove this restriction and the black band ore then became very suitable for the furnace charge.

The Scottish works rapidly adopted hot blast practice when it was recognised that this made possible the use of the local iron ore and coal deposits. It was fortunate for Neilson that he had patented his development, for in 1843 he had to resort to legal action against the Association of Scottish Ironmasters to enforce payments of the royalties. The English and the Welsh Ironmasters were initially less receptive of the new practice, for they did not envisage comparable improvements if a hot blast was applied with the higher quality coking coals and more reducible iron ores that they were using. Some works in Wales did change to hot blast operation when they found that the local anthracite coal could also be substituted for coke in the blast furnace, but elsewhere the works were very slow to adopt the new practice. In Scotland, however, the output of pig iron increased rapidly with the use of local raw materials. This was accompanied by a sharp fall in the costs of production and resulted in the capture of a larger share of the market for pig iron. About 500,000 tons of pig iron was produced from hot blast furnaces in 1841, of which 60% was made in Scotland where all the furnaces had been converted. Many companies south of the Scottish border were now forced to adopt the practice to avoid insolvency. Almost all the furnaces in Britain had changed to hot blast operation by 1850. But eight furnaces at the Low Moor Iron Company were using a cold blast in the 1870s (Ref. 12) and four furnaces were still making cold blast iron in 1895 for the production of rolls and special castings.

The traditional solid cast iron tuyeres had only a short life when used with a hot blast. John Condie introduced the first water cooled tuyeres on his furnaces in Scotland to improve the durability. In the initial form a wrought iron tube, through which water was passed, was coiled round a truncated cast iron cone. Shortly afterwards a hollow tuyere was introduced, with two truncated cones joined at the ends and with water inlet and outlet pipes. Traditionally, the tuyeres had been coupled to the bustle main via leather bellows, but these were of no use with hot blast and they were replaced by cast iron gooseneck connections.

Probably the first systematic investigation of the gas reactions which occur within a blast furnace was reported in 1845 by Bunsen and Playfair. Using a probe that descended with the charge, they sampled the gas at various heights in a 12 m tall furnace in which a roasted carbonate iron ore was being smelted with the coke equivalent of 2.8 tons of raw coal per ton of pig iron. Their principle conclusion was that only 18.46% of the thermal energy was utilised for the smelting of the ore and 81.54% was lost. They implied that the whole of the energy could be utilised for the reduction and melting operations if the furnace was designed and operated more efficiently. This became the target for development, which prevailed for the next twenty-five years.

Bunsen and Playfair reported a CO/CO$_2$ ratio of 3.21:1.0 in the top gas, which is approaching twice the ratio that is achieved in present day practice and attention was drawn to the energy available in this gas which could be used for other purposes. All the furnaces in use at that time were operated with an open top. The gas
was released to the atmosphere via a cylinder, or tunnel head, of smaller diameter than the top of the stack, which extended through the charging platform (see Fig. 1). The gas was burned at the top of the cylinder and sometimes air was admitted below the tunnel head to improve the combustion. The flame provided free illumination for the works and for the surrounding district.

Attempts were made from time to time to utilise some of the energy available in the off-gas for other purposes. J. P. Budd patented an arrangement in 1845 to raise the temperature of the blast by using a stove which was heated by the combustion of the off-gas. No means had been found at that time to collect the gas and to transfer it to ground level, so the stove was mounted on the charging platform at the furnace head. The problem of gas collection was solved in 1850 when G. Parry introduced the bell and hopper arrangement to close the furnace top at the Ebbw Vale works in South Wales. A gas off-take located below the bell but above the stock line was introduced to transfer the gas to ground level. A few works adopted this arrangement and began to install gas-fired boilers and blowing engines, but the majority of ironmasters were reluctant to adopt the closed top, claiming that combustion of the gas above the charge improved the up-draft inside the furnace and aided smooth operation. Even Lowthian Bell, one of the leading authorities on nineteenth century blast furnace practice, was advocating only semi-closed top operation with the retention of the tunnel head, eight years after Parry's invention. Most blast furnace plants still used coal firing for the blowing engines and for heating the hot blast stoves in the late 1860s, but worries about the exhaustion of the coal reserves and a possible coal shortage arising from the rapid growth in iron production brought about a change in attitude. Closed top operation (Fig. 3) was almost universal in England and Wales by 1881 (Ref. 4), but four years later about forty open topped furnaces were still in use in Scotland.

The introduction of the bell and hopper vastly improved the environment for the workers who were employed to transfer the charge in wheelbarrows from the top of the hoist to the furnace head. With open top operation the charge was tipped into one or more chutes in the tunnel head, through which the off-gases were passing continuously. The workers were only exposed to the heat and fumes when the bell was lowered with the single bell and hopper arrangement. The introduction of the double bell arrangement from the early 1880s almost completely eliminated gas release at the charging platform. Several decades elapsed, however, before the introduction of mechanical charging began to eliminate the need for manual labour at the furnace head and hand charging was continued, for example, at the Parkgate Iron and Steel Company until the late 1940s.

The pipe stove had evolved into a more durable form by midcentury, but the maximum obtainable blast temperature was still limited by the strength of the cast and wrought iron assemblies used for the construction. The blast was eventually raised to a higher temperature through the adoption of a radically different approach. Edward Alfred Cowper, a steam engineer, had collaborated with the Siemens brothers in some of their projects and he recognised the potential of their regenerative system for heating the blast. His first design (British Patent 1404, 1857)
used two cylindrical chambers containing refractory chequers, which were built to approximately the same height as the blast furnace. One chamber was absorbing heat from the fan-assisted combustion of the furnace off-gas whilst the other transferred the absorbed heat from the chequers to the air blast. The roles were interchanged at two hour intervals.

The stoves and the blast main were refractory lined, allowing the air to be heated to higher temperatures than could be attained with the cast iron stoves. By 1860, the maximum blast temperature had been raised to 750°C (Refs. 19 and 20) and Cowper showed that the amount of solid fuel required in the furnace could be decreased by about 18% when the blast was heated to this temperature. Problems were encountered, however, with the blockage of the chequer work by the dust that was carried over in the blast furnace gas. This was eventually solved by the interposition of a dust catcher between the blast furnace down-comer and the stoves.
Meanwhile, Thomas Whitwell designed a different form of regenerator, which was claimed to simplify the removal of dust (British Patent 2897, 1865). These two versions of the hot blast stove were first applied to furnaces in the North East Coast district, where the initial development work was undertaken. Elsewhere, there was a reluctance to adopt the new technique similar to that which had been shown earlier to Neilson’s work. By 1882 only fifty-one furnaces in Britain were equipped with Cowper stoves and sixty-one were using the Whitwell version.\textsuperscript{15} About half of the total number of blast furnaces were still equipped only with pipe stoves at the end of the century.

The average fuel consumption for British furnaces decreased markedly during the 1870s, prompted by the increasing concern that the coal stocks would soon be exhausted. The now widespread adoption of closed top operation and the more limited application of the hot blast stoves aided this improvement. The average fell from 3 tons of coal (1.5 tons of coke) per ton of pig iron in 1869 to 2.2 tons of coal (1.1 tons of coke) per ton by 1880. It remained at about that level for the next fifty years,\textsuperscript{21} although the more efficient plants were using only about 1.5 tons of coal per ton of iron by the end of the century. Thus, between 1800 and 1880 the energy efficiency in smelting had increased by about eight fold.

The arguments concerning the minimum fuel consumption that could be achieved in a blast furnace were placed on a more realistic footing in 1870. This was stimulated by a presentation by the proprietor of the Ormesby works of Cochrane and Company at Middlesbrough, who had installed Cowper and Whitwell stoves at his blast furnace plant. Resurrecting the earlier arguments based upon driving reactions to completion, he argued that with a ‘superheated’ blast it should be possible to operate a blast furnace with a consumption of only 0.65 tons of coke per ton of pig iron.\textsuperscript{22} Lowthian Bell refuted this contention with probably the first metallurgical application of the Law of Mass Action, which had been formulated a few years earlier by Guldberg and Waage. Bell calculated that equilibrium constraints prevented the utilisation of more than about 53\% of the energy available from the coke included in the burden.\textsuperscript{23,24} His computations were supported by systematic observations made during the development and operation of larger furnaces smelting Cleveland iron ore at the Clarence works in Middlesbrough. He found that the fuel consumption fell as the height of the furnace was increased until a stage was reached where the temperature of the gas, as it emerged from the burden, had fallen to about 300°C. There was no gain in fuel efficiency with any further increase in height beyond this stage. He concluded that the limit of the reducing power of the gas in a furnace of optimum height is attained when the CO/CO\textsubscript{2} ratio in the off-gas is between 2.0:1.0 and 2.2:1.0. This conclusion was subsequently expanded by the first published consideration of the optimum balance between the two mechanisms of direct reduction of the ore by solid carbon and the gaseous or indirect reduction reactions.\textsuperscript{25} Bell was initially opposed to the use of the highest blast temperatures that could be attained when Cowper stoves were hard driven and his calculations were based on a use of a blast temperature not exceeding 600°C. The estimates of the minimum attainable fuel levels were gradually revised down-
wards over the next decade, however, as other operators gained experience of smelting with the blast heated to higher temperatures.

An improvement in energy efficiency was also obtained through developments in the methods used for coke manufacture. Throughout the nineteenth century, coke was produced almost entirely in beehive ovens and, despite progressive improvements in performance, only about 60–65% of the weight of the coal was recovered as coke. The by-products were lost to the atmosphere. A battery of coke ovens designed by a Belgian engineer, Evence Coppee, which gave yields of up to 75%, was installed at a works in Sheffield in 1872. It was closed down two years later because the quality of the coke was regarded as inferior to that from the beehive ovens, but a similar installation in 1874 at the Ebbw Vale works was commercially more successful. A battery of Simons Carves ovens was installed in 1882 at the Darlington collieries of Pease and Partners and the first Otto coke ovens in Britain were built in 1898. Gas holders and by-product lines by then were established features of a coke oven plant. Up to the end of the century, however, the vast majority of iron manufacturers still contended that coke produced in beehive ovens was a more suitable fuel for the blast furnace.

2.1.3 Chemistry of the Process
In marked contrast to the steady improvement in thermal efficiency achieved during the century, the ability to control the chemical composition of the iron progressed only slowly and evolved mainly as a result of trial and error developments. By the 1860s, it was recognised that magnesia was an undesirable element in the charge, for it could make the slag too viscous, whereas manganese oxide improved the fluidity. In general, however, the effect of composition on the slag fusion temperature was only vaguely understood. Each ironmaking district evolved a practice for burden preparation and flux additions appropriate to the type of local iron ore that was being used to ensure that a slag would be formed which would flow freely from the furnace. Most works had developed a means of controlling the process to produce grey, white or intermediate grades of pig iron, but there was no scientific basis for the decision-making.

It was well recognised that all the phosphorus in the charge was transferred to the iron, none was retained in the slag, and that a high operating temperature increased the silicon content of the iron. By midcentury, the formation within the furnace of a volatile silicon monoxide had been postulated. On the basis of extensive observations, George Parry noted that the amount of sulphur transferred from the charge to the slag increased with the manganese oxide content of the charge.

The understanding of the chemistry of the reactions was increased very considerably as a result of the systematic investigations of the process that were undertaken from 1860 onwards by Lowthian Bell. The first volumes of the Journal of the Iron and Steel Institute were largely devoted to detailed reports of his findings, which were published subsequently as a book. This stimulated wider consideration of the factors controlling the composition of the iron. The consistency of the product then slowly began to improve, but at the end of the century there were still
marked differences between the quality of the products from the best and the worst plants.

2.1.4 The Ironmaking Districts

The relative importance of the various ironmaking districts in Britain varied markedly during the course of the nineteenth century. New regions emerged to challenge the supremacy of those with a longer history and the major locations at the

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end of the century bore no resemblance to those that were dominant at the begin-
ning, as is evident from the data presented in Table 3.

When charcoal was the only fuel used in the blast furnaces, the industry had
been restricted to locations near to both forests and iron ore deposits. Before the
introduction of steam-powered blowing engines, the location was restricted also to
places where an adequate supply of water was available to turn the water wheels
which operated the bellows to produce the air blast. By the late eighteenth century,
Shropshire was one of the few areas where sufficient timber was still available and
it had become the principle iron-producing region in Britain. Almost as many fur-
naces were located in South Yorkshire and Derbyshire, but the combined output
from these two districts had fallen below that from Shropshire.

Most of the furnaces in Shropshire had changed to coke smelting with a marked
increase in productivity by the dawn of the nineteenth century, but by that time the
district had been pushed into second place owing to more rapid growth of the
industry in Wales. A few furnaces had been erected at Brymbo and Ruabon in
North Wales, but the major development was located on the northern edge of the
South Wales coal field to exploit the local coal and iron ore deposits. The main con-
centration of works was in and around Merthyr Tydfil. The Dowlais and Cyfarthfa
works had been started there in 1758 and 1765 respectively and others were opened
at the turn of the century. The output from all the works in the locality was only 250
tons of pig iron per week in 1795, but by 1803 the Cyfarthfa works was described
as the largest iron works in Britain and twenty-two blast furnaces had been erected
in the area.2 Other works in the locality at Tredegar, Ebbw Vale and Blaenavon also
built new furnaces to expand pig iron production.

The British engineering industry had been largely dependent on the import of
good quality malleable iron from Sweden and Russia during the eighteenth cen-
tury, but the situation was changed by the disruption of supplies and by the impos-
sition of a high import duty during the Napoleonic wars. British pig iron
manufacture expanded rapidly to fill the gap and eighty-five new furnaces were
blown in between 1800 and 1806. Britain had become the dominant producer of pig
iron in Europe when peace was restored. By that time the works in the Merthyr dis-
trict were producing 20% of the total British output.

Elsewhere, the most spectacular rate of growth in this period was in the area of
South Staffordshire and North East Worcestershire, which became known as the
Black Country. A 9m thick seam of good coking coal interspersed with coal-
measure iron ores had been discovered there and the number of blast furnaces in
the district increased from six to forty in an eighteen year period up to 1806.2 By
1815 two thirds of the British pig iron production came from South Wales and the
Black Country.13

Many furnaces were blown-out during the industrial recession, which started in
1815, following the restoration of peace. Most of the works in Shropshire were
equipped with only small furnaces and the equipment was mainly obsolete. They
were affected particularly severely by the fall in demand and the district continued
to decline in relative importance. In marked contrast, the output from the Black Country had almost doubled again by 1823.

The pig iron made during the first half of the century was extracted mainly from sideritic, coal measure iron ores, which contained 30–45% of iron after roasting. Smaller quantities of hematite ore were mined in West Cumberland and the Furness district of Lancashire. Some hematite ore was still obtained from the Forest of Dean and from Cornwall, Devon and Somerset. Very little of this ore was smelted in proximity to the mines and it was mainly transported by ship and by canal barge to works in Wales and in Scotland.

Only one new works was opened in Scotland during the first quarter of the century and the total number of furnaces in the locality actually decreased during a recession in the early 1820s. The situation changed rapidly with the introduction of the hot blast practice and with it the ability to smelt the black band ironstone. Twenty-four new ironworks were opened in Scotland and the output of pig iron had increased five fold within ten years of the publication of Neilson's first patent.\(^5\) By the mid 1830s Scotland had become the third largest production centre for pig iron in the United Kingdom and by 1845 it had overtaken Staffordshire to move up into second place.

The adverse trading conditions created by a recession, which started in 1839, coupled with the surge in production from Scotland, had serious implications for the works located in the Black Country. The richest coal seams in the region had now been severely depleted and the local coal measure iron ore supplies were nearing exhaustion by midcentury. Production was maintained only by transporting ore from North Staffordshire, Warwickshire and eventually from the new mines that were being opened up in Oxfordshire and Northamptonshire. This marked the beginning of the decline in the relative importance of the Black Country as a source of pig iron, although the peak production from the region was not attained until 1874 when 110 furnaces were in blast. One factor that prolonged the survival of the industry in the region was the generally high quality of the pig iron produced, which was regarded as highly suitable for conversion into wrought iron. In marked contrast, it was difficult to convert the Scottish pig iron into wrought iron and it was used mainly for castings. But this advantage became less important as the bulk steelmaking processes were developed and the demand for wrought iron began to decline. Only twenty-eight of the eighty-five furnaces remaining in the Black Country were still in blast in 1886 (Ref. 6) and nine of these had been blown out by 1895.

The traditional ironmaking districts found a new outlet for their products during the 1840s when a demand arose for wrought iron rails for construction of the new railway networks. For a time, the works located in South Wales and Monmouthshire became the major suppliers. The Dowlais works had displaced the neighbouring Cyfarthfa plant from its prime position and, with eighteen blast furnaces producing 1600 tons of iron per week, it had now become the largest iron works in the world. Over one third of the total pig iron output in Britain was made in Wales during the 1840s. Production in the locality peaked, however, a decade
later and then began to fall because the local iron ore deposits were nearing exhaustion. The works, which were located in the area known as the Heads of the Valleys, were connected to the South Wales coast by canals and by the Taff Vale railway, which was opened in 1841. But the operations were less profitable when most of the iron ore had to be transported to the works from the coastal ports and the products had to make the same journey in reverse. Scotland had displaced Wales as the largest producer of pig iron by the mid 1860s. The Scottish black band ironstone deposits were also nearing exhaustion, however, and, by the end of the decade, Scotland had surrendered first place to the newly developed North East Coast Region.

A small but important malleable iron industry had been established early in the eighteenth century in the vicinity of Newcastle-upon-Tyne. For raw materials, it relied mainly upon imports of charcoal iron from Sweden and Russia, but some pig iron was produced from ores mined locally in two small blast furnaces, which were built in 1800 by the Tyne Iron Company. Other small works were established in the vicinity during the first quarter of the century. Isaac Lowthian Bell designed a new blast furnace in 1844 for the Walker Iron Works and then, with his brothers, he took over the lease of the Wylam Iron Works. Both plants were located on the banks of the river Tyne. This was the start of the development of the iron industry on the North East Coast region.

The Consett iron works (originally named the Derwent Iron Company) started production in County Durham in 1846 and two years later Henry Bolckow and John Vaughan opened the Witton Park works at Bishop Auckland. These works were supplied with coking coal from Durham and a low grade, almost self-fluxing spathic iron ore, which was produced in small quantities from mines at Grossmont and Skinningrove in North Yorkshire.

Deposits of iron ore in the Cleveland hills had been identified in 1812, but they were not fully exploited until John Vaughan discovered the Eston outcrop in 1850. Almost immediately afterwards, a cluster of new works sprang up on the nearby mudflats bordering the river Tees at Middlesbrough. These included the Clarence works, founded by the Bell Brothers in 1853, Bernard Samuelson's South Bank (1853) and Newport (1863) works and the Middlesbrough (1840) and Eston (1852) Iron Works built by Bolckow and Vaughan. Thirty furnaces had been built within a radius of 10 km from the original village of Middlesbrough by 1855 and seventy-five furnaces were in blast four years later in the North East region. From a small beginning, the output of pig iron from the region had risen rapidly to over 1 million tons by the mid 1860s and now exceeded the production from each of the other regions in Britain. Under the leadership of Lowthian Bell, the works in the district set the standards for the development of larger furnaces. By 1887, the average annual output from each of the furnaces was 27,000 tons, when the average output for all furnaces in Britain was only about 18,000 tons. The district was then producing more than one third of the total British pig iron output.

The largest deposits of hematite iron ores were located in Cumberland and the northern tip of Lancashire. These ores had an average iron content of over 55%,
whereas the coal and clay band ores rarely contained more than 30% of iron, but they occurred in isolated deposits and not in massive seams. Consequently, their exploitation developed only slowly. Four small furnaces on the North West Coast were producing iron from the local hematite ores in 1800. The total output was only a little over 2000 tons per annum. It remained insignificant until the 1860s, when the demand for pig iron with a low phosphorus content suitable for refining in the new Bessemer converters led to a rapid expansion of the industry. The initial growth took place mainly in the vicinity of Barrow in Furness, where Henry Schneider had discovered a bed of hematite ore in 1850 and Messrs Schneider and Hannay built the first blast furnace at Barrow in 1859. Ten furnaces, 16 m high, were in blast by 1863. With an annual output of over 60,000 tons, the plant had captured from Dowlais the title of the largest ironworks in the world. Four more furnaces had been built by 1874, by which time the ownership had changed and the plant was now called the Barrow Hematite Steel Company. These furnaces were still operating with a semi-closed top in 1880, the off-gases being partially recovered with the aid of a brick dome which was erected on the top of the furnace.

Further north along the coast, the first furnace in Cumberland was built in 1841 for the Whitehaven Iron Company and more furnaces were built in the mid 1850s in the vicinity of Workington. Over fifty furnaces had been erected in Cumberland by 1870, but only three of these operated with a closed top and with off-gas recovery. The ore deposits in this region occur as isolated metasomatic pockets of hematite in heavily faulted limestone beds. Mineralogical surveys in the 1850s located new deposits suitable for development and many new mines were opened. The Millom mine was opened in 1855 and continued in production for 100 years. The local ore production increased from 200,788 tons in 1855 to top 1 million tons in 1870 and peaked at 1.6 million tons in 1889 when fifty mines were in operation. The output slowly declined thereafter and nearly half the pig iron made in the district at the end of the century was produced from ore imported from Spain which had a higher iron content. The region also possessed ample stocks of good coking coal. Coal production expanded initially at a similar rate to the production of iron ore, but the output continued to grow after the recovery of ore from the mines had started to decline and the district remained self-sufficient for fuel supplies.

The third region to emerge as a major new iron producer was based on the discovery of extensive ore deposits in Lincolnshire and Northamptonshire. Iron had been produced from local ores in Lincolnshire during Roman times, but the ore bed was only rediscovered when a railway cutting was being excavated in 1859. Tests carried out in a furnace at Elsecar, near Barnsley in South Yorkshire, showed that the calcareous ore could be smelted satisfactorily if it was mixed with Yorkshire coal measure ores and for several years all the ore produced from the deposits was transported for smelting in South Yorkshire. The quantity of ore mined increased from 2000 tons in 1859 to 16,000 tons in 1860 and then to over 250,000 tons in 1869.

The Milton iron works, which was opened in 1861, was the first to start production on the ore field. The North Lincolnshire Iron Company erected two furnaces at Scunthorpe in 1866. The Frodingham Iron Company also built two furnaces in that
year and two more were added in 1870. Twenty-one furnaces had been built in the area, but only nine of these were in blast when the Appleby Iron Company blew in its first furnace in 1877.

The siliceous oolitic Northampton ore bed was also rediscovered during the excavation of railway cuttings. The first iron works to use the ore was erected at Wellingborough in 1852, but the output was very small until the company opened a larger works in 1867 at Irthlingborough. Five other companies built blast furnace plants on the ore field during the next decade. In comparison to the North Lincolnshire works, however, the total output was small and the major exploitation of the ore for local smelting was delayed until the twentieth century.

The phosphorus content of the pig iron produced from the Lincolnshire and the Northamptonshire ores was lower than that made from the Cleveland ores. Consequently, it was more suitable than the latter for the production of castings and for conversion into malleable iron. Conversely, it was less suitable for refining in the basic Bessemer process. Production of the local pig iron only increased rapidly, therefore, when the basic open hearth process was developed.

Despite the development of the new iron ore mines in Cleveland, Cumberland, Lincolnshire and Northamptonshire, the rate of extraction of the ore from the ground did not keep pace with the rate of growth of pig iron production. Thus, 10.48 million tons of ore was mined in Britain in 1856 and this satisfied the indigenous demand. Twenty years later home ore production reached 16.73 million tons, but this had to be supplemented with imports of 672,000 tons, which came mainly from Spain where new mines were opened after the export duty had been removed in 1870. Almost half of the imported Spanish ore was consumed in three blast furnaces, which had been erected by Bolckow Vaughan at their Eston works to produce acid Bessemer grade pig iron. By 1880, when the basic Bessemer process was being developed, home ore production had increased only slightly to 17.50 million tons while imports had risen to 2.6 million tons. The proportion of pig iron produced from imported ore continued to increase to the end of the century and beyond.

During the course of the century, first Wales, then Staffordshire and Scotland had become major pig iron production centres. But their relative importance declined, first when the Cleveland ore field was exploited and then as the demand arose for a pig iron that was suitable for steelmaking by the acid processes. They had declined markedly by the time that a new requirement arose for a pig iron suitable for refining in the basic steelmaking processes. The Lincolnshire and Northamptonshire ore fields were being developed to satisfy the latter requirement, but they still had a long way to go to reach their full potential.

2.2 Direct Reduction

The reduction of iron ores in the solid state to produce metallic iron intermixed with the gangue minerals, but relatively free from elements in solution other than carbon, is usually regarded as a twentieth century invention. It is actually a devel-
opment from the early bloomery process, with the essential difference that the ore is reduced below the temperature at which the gangue begins to melt. The principles which underlie the modern direct reduction processes were identified through a series of investigations that started at the end of the eighteenth century.

One of the first schemes proposed for direct reduction was described in a patent issued in 1792 to Samuel Lucas. This described a procedure in which a refractory pot was filled with a mixture of crushed iron ore and charcoal and then covered with a lid to prevent the ingress of air. The pot was heated in a reverberatory furnace until the reduction was judged to be complete.

Adrian Chernot began experiments in 1823 at the works of Bagney and Company in Paris. A British patent, issued in 1845 and based on his work, outlined a procedure for the reduction of the ore with charcoal in a hearth surmounted by a conical top. In a subsequent modification, the charcoal was replaced by a continuous flow of carbon monoxide. After passage through the kiln, the gas was reformed for reuse by circulation through a retort containing carbonaceous matter at a red heat. Once daily, a quantity of sponge iron was withdrawn from the bottom of the furnace and additional ore was then charged through the top to give a semi-continuous process. The patents provided for the use of electro-magnets to separate the gangue from the reduced ore.

In an attempt to economise on fuel consumption, E. A. L. Belford obtained a patent in 1854 for a process in which pulverised ore was reduced by charcoal in a tubular vessel and the product was transferred to a crucible for melting while it was still hot. This theme was carried further by Isaac Rogers, whose 1855 patent described the use of a horizontal kiln which was heated externally. A mixture of pulverised ore and charcoal was moved through the kiln by a helical screw conveyor and the reduced ore was fed directly to a reverberatory furnace. None of these proposed methods achieved commercial success during the lifetime of their inventors.

After he had developed the open hearth steelmaking process, C. W. Siemens reactivated some of the earlier direct reduction ideas in an attempt to produce a feedstock, suitable for use in his furnace, direct from iron ore without the need for a blast furnace. Much effort was expended in an attempt to achieve this objective. His first patent on the subject, issued in 1867, described an operation with two vertical retorts, externally heated and mounted above the roof of an open hearth furnace. Producer gas was fed counter current to the descending column of ore, which was discharged after reduction onto a bed of molten pig iron in the open hearth furnace. Periodically, the sponge iron flow was halted by the insertion of a plate across the bottom of the retort while the steel heat was finish-refined and tapped from the furnace.

A second patent, issued in the following year, described the construction of a horizontal rotary kiln, 2.4 m in diameter and mounted on rollers above regenerator chambers (Fig. 4). Using a gas and ore feed similar to that described in his previous patent, a relatively high degree of reduction was obtained. But the trials were discontinued, as the sponge iron was not suitable for use in the acid open hearth
process because it was too heavily contaminated with sulphur absorbed from the producer gas.

The original experiments were conducted at the Siemens Landore works in Swansea. More extensive trials were started in 1873 at Towcester in Northamptonshire, where Siemens built a plant containing three rotary kilns to reduce the plentiful supplies of iron ore fines which were available in the locality. Unfortunately, he did not realise that the ore fines he was using had a relatively low iron content, resulting in a high fuel cost per ton of sponge iron produced. The project was judged not to be viable because of this and the Towcester works was closed down in 1878. A further attempt was made to develop a rotary hearth kiln at the Landore works in 1880, but the experiments were terminated by the death of Siemens in 1883. Although commercial success eluded him, the principles of the modern direct reduction processes had been clearly defined and the present practices bear significant resemblance to these early endeavours.

2.3 Wrought Iron Manufacture

2.3.1 The Cort and the Hall Processes

British Patent 1420, issued in 1784, was granted to Henry Cort for a puddling process 'to convert pig iron into malleable iron by means of a flame of pit coal in a common air furnace and to form the metal into bars by the use of rollers in the place of hammers'. He had obtained a patent for rolling iron with grooved rolls in the
previous year. Prior to Cort's work, malleable iron had been produced mainly in the finery furnace, which could only use charcoal as a fuel because the pig iron charge was melted in contact with the fuel. Combustion of the fuel in Cort's reverberatory furnace took place on a grate that was separated from the melting hearth by a refractory bridge and the roof above the grate sloped downwards towards the hearth to deflect the flame onto the metal. Raw coal could then be used for heating, for the ash and the sulphur in the coal did not contaminate the metal.

The initial experiments were conducted at Fontley in Hampshire, but the first successful commercial production was located at the Cyfarthfa works in South Wales. Furnaces were installed also at the Penydarran works, nearby, and at Coalbrookdale. Cort's experiments at Fontley were halted when the mill was destroyed by fire in 1796, four years before his death. There was a relatively slow take-up of the process elsewhere, for the ironmasters were reluctant to pay a royalty of £0.25 per ton of bar iron produced. The patent was invalidated, however, when Cort's business partner, Adam Jelicoe who had financed the patent application, died insolvent. Freed from the payment of royalties, the attitude of the ironmasters changed and there was a rapid adaptation of the process. This change was encouraged by the decline in the volume of imports from Sweden and Russia, which followed the imposition by the government of an import tariff during the Napoleonic wars. Ninety-four puddling furnaces were in operation by 1812 and the Cyfarthfa works produced over 10,000 tons of puddled wrought iron in that year. By the time that peace was restored in 1815, the output of wrought iron had increased six fold from the level that had been achieved in 1790 and Britain had become the major producer of bar iron in Europe.

When Cort developed his process, he used silica sand to line the hearth of the furnace. This did not fuse completely at the relatively low temperatures to which the furnace was heated. Hammer scale was added periodically to the bath as an oxidant when the pig iron was molten and the bath was stirred with a rabble to bring the slag into more intimate contact with the metal and accelerate the oxidising reactions. Care was required, however, to restrict the turbulence caused by the oxidation of the carbon in the cast iron charge, for the semi-fused hearth could be severely eroded by a violent carbon boil. The ferrous silicate slag, which was formed by oxidation of silicon from the charge, soon became saturated with silica from dissolution of the hearth. Consequently, it could become quite viscous in the intervals between the additions of hammer scale. The molten iron also became very viscous as the carbon was oxidised to a low level and the melting point increased towards the temperature in the furnace hearth. When this stage was reached, the rabbles were used to work the slag into three or four 'puddler's balls', containing the agglomerated iron particles. These were removed, in turn, from the furnace for consolidation by hammering or rolling.

The preferred charge was a white pig iron with a relatively low content of carbon and silicon. A higher temperature was required in the furnace to melt a grey iron charge, but the melt then became very fluid, in contrast to the pasty state through which a white iron passed during melting. There was consequently a greater risk
of penetration of the hearth. A finery hearth was frequently retained for the pre-
treatment of grey irons, where the iron was melted on a coke bed and part of the
silicon and carbon was oxidised out from the iron before it was fed to the rever-
beratory furnace.

Cort's process was a major advance, when compared with the older refining pro-
cesses, but for a long time the quality of the product was regarded as markedly
inferior to iron from the finery, requiring extensive mechanical working to consoli-
date the metal. It was relatively inefficient, for large amounts of iron were lost in the
fayalite-type slag. In the earlier applications of the process, 1 ton of malleable iron
was produced from about 2 tons of pig iron. The yield slowly increased as know-
how accumulated, but the consumption did not fall below about 1.75 tons of pig iron
per ton of wrought iron when a silica hearth was used. Although the productivity
was significantly higher than with the finery operations, only four heats, each weigh-
ing about 125 kg, could be worked in a furnace in a 12 hour shift (i.e. the normal
working day), as a new silica hearth had to be prepared after each heat. The output
was approximately doubled when the pig iron was pre-treated on a finery hearth.²

Numerous attempts were made to improve the efficiency of puddling and many
of the early trials were conducted in South Wales. Samuel Baldwyn Rogers of Nant-
y-Glo in Glamorganshire attempted to improve the life of the hearth and increase
the rate of refining by substituting a cast iron bottom protected by a layer of iron
oxide for the lining. Trials were eventually carried out at the Ebbw Vale works in
1818, but they were not judged to be successful.¹

A parallel development was under way at the Barrow and Hall works at Tipton
in Staffordshire, where, in 1811, Joseph Hall with his partners, Richard Bradley and
William Barrows, had also begun trials with alternative hearth linings. After almost
twenty years of development work, Hall patented the user of a hearth lined with
roasted cinder taken from the puddling furnace.⁶ This variant was soon adopted by
the industry and the puddling process rapidly evolved into a form that continued
in operation with only minor modifications beyond the end of the century.

The bottom and sides of the Hall furnace were contained by air-cooled plates,
which chilled the lining and helped to extend the life. The lining material was pre-
pared by collecting the tap slag from a furnace and roasting it in a kiln for several
days. The more fusible portions of the slag melted during the treatment and were
allowed to drain out of the kiln. The ferrous oxide in the remainder was oxidised
to ferric oxide or magnetite. This raised the melting point of the cinder above the
maximum temperature that was normally attained in the puddling furnace. The
roasted product, which was referred to as bulldog, was used to ram a lining over
the bottom and the sides of the hearth and it was consolidated by sintering after the
pores had been filled with a paste of hematite ore.

A typical charge might comprise of 200 kg of pig iron and 50–80 kg of hammer
scale. This scale, which normally contained about 70% of low melting point ferrous
silicates, melted rapidly and a sufficient quantity was added to ensure that as the
iron melted it was completely covered by a fluid slag. The charge was fully molten
in about 30 minutes. The carbon boil started while the metal was still melting and
was characterised by the appearance of small blue flames on the surface of the slag. These flames were known as puddler's candles. The charge was rabbled continuously from the stage when the flames appeared until refining was completed. The boil became progressively more intense, causing the slag to form a foam. Part of this foaming slag was frequently allowed to flow out from the furnace over the door sill, taking with it some of the impurities that had been oxidised out from the iron. A more vigorous boil could be tolerated without fear of damaging the cinder hearth, so the refining could be completed in a shorter time. Thirty to forty minutes after clear melt the iron started to become pasty owing to the loss of carbon and small globules of iron began to appear at the slag surface. Full heat was applied to the furnace when this stage was reached and was maintained for a short time to raise the furnace temperature while the iron was worked up with rabbles into puddler’s balls. The ferrous silicate slag remained fluid throughout the operation. Hence, the practice introduced by Hall became known as wet puddling in contrast to the dry process, which Cort had invented, where the slag became very viscous towards the end of the refining stage. A wider range of pig iron compositions could be puddled satisfactorily on a cinder hearth, so the finery pretreatment became redundant for preparing the puddling charge. Some fineries were still being operated in midcentury, however, to produce malleable iron for use in applications requiring a high purity, such as for the production of tin plate.

In the original Cort process, the thermodynamic activity of any ferrous oxide, which was present in the hearth either from the mill scale additions or from atmospheric oxidation of the charge, was lowered by solution in a silica-rich slag. The silica was supplied to the slag by oxidation of silicon from the pig iron and from sand that adhered to the iron when it was removed from the pig beds, but mainly from the erosion of the silica hearth. With wet puddling, the silica supply was limited to the first two of these sources and the slag volume was correspondingly reduced. The ferrous oxide in this slag would have an activity closer to unity and could, therefore, be readily reduced back to the metallic form by oxidising the carbon and the other metalloids in the pig iron. At the end of the refining stage the damper was usually lowered to fill the furnace with smoke and change the atmosphere from strongly oxidising to mildly reducing while the puddler’s balls were awaiting removal from the furnace. This also aided the metal recovery. The metal loss in wet puddling was less, therefore, than with the dry process and when it was fully established, the Hall practice typically consumed only 1.3 tons of pig iron for the production of 1 ton of malleable iron.¹¹

The more fluid slag allowed the operations to be conducted at a slightly lower temperature and the carbon boil provided part of the heat requirements. Less time was required to repair the cinder hearth between heats and the refining reactions occurred more rapidly, so seven heats could be processed in a 12 hour shift. As a result, the fuel consumption fell from about 4 tons of coal per ton of malleable iron with Cort’s process to an average of 2 tons with the wet puddling technique when it was fully operational. By the 1880s this had fallen further to 1.0–1.25 tons of coal per ton of iron.¹⁵
2.3.2 Chemistry of the Puddling Process

The wet puddling process evolved as a result of visual observations and trial and error experiments. Few iron works employed a chemist, even at the end of the century, and the occasional reported analyses of samples of metal and slag taken from a puddling hearth were usually performed in academic or other independent laboratories. An understanding of the reaction mechanisms only began to emerge from about 1860 onwards. It was generally recognised by that time that on a cinder hearth the silicon was almost completely eliminated from the pig iron before the carbon started to oxidise. A decade later, C. W. Siemens resolved arguments about the mechanism of oxidation by isolating the slag from the atmosphere with a layer of molten glass to show that the impurities could be removed entirely from the metal by the oxygen supplied from the slag.32

In marked contrast to the Cort process, a basic slag could be formed with a cinder hearth into which phosphorus could be transferred during puddling. In trials conducted at the Ebbw Vale works in 1861, G. Parry claimed that two thirds of the sulphur and up to 80% of the phosphorus could be removed from the metal by ‘adding as much lime as the slag would bear without increasing its viscosity’.33 There seems to have been little interest shown in this work. More interest was shown when J. E. Stead demonstrated that more than 70% of the phosphorus in the pig iron could be transferred into an almost lime-free slag before the start of the carbon boil. The extent of the removal was diminished as the silicon content of the charge was increased,34 but manganese was shown to have a lesser retarding effect. Most of the phosphorus could then be removed from the furnace if the slag was allowed to overflow over the door sill or through a slag tap hole. Some phosphorus was found to be desirable in the slag at the end of refining to retain fluidity and to aid the exudation of the slag from the metal during the subsequent forging operation. Stead showed, however, that phosphorus could revert from slag to metal if a very impure slag remained in the furnace at the end of the process. In a subsequent report,35 he claimed that just over half of the sulphur in the pig iron could be removed into the slag or evolved as sulphur dioxide.

In view of the neglect of chemical analysis and control procedures, it is not surprising to find that the composition of the malleable iron varied over quite a wide range. Analyses performed in later years have shown that the carbon content was generally in the range 0.15–0.30% together with 0.10/0.25%Si, 0.01/0.15%S and 0.05/0.20%P. In modern terminology this would be classed as a mild steel. The cinder was often richer in iron than the indigenous iron ores and was, therefore, recycled in the blast furnace charge. The consequent recycling of the phosphorus pentoxide absorbed by the cinder had important consequences at a later stage when the acid Bessemer process was being developed.

2.3.3 Modifications to the Puddling Furnace

Most of the puddling furnaces which were in use at the end of the nineteenth century showed comparatively little difference from the design that had evolved by
the 1840s. Many attempts were made to develop a more efficient form, but in general these were not successful. In some works, the furnace was extended to beyond the usual $5\,\text{m}^2$ bath area to allow pre-heating of the next charge whilst the current charge was being worked. The air for combustion was sometimes supplied under pressure to increase the rate of combustion.

An attempt was made at the Round Oak Iron Works to apply the Siemens regenerative principle to the heating of the puddling furnace, using a furnace similar in construction to that shown in Fig. 5, but the initial trials were not encouraging. The

Fig. 5 Siemens's regenerative puddling furnace (F. Kohn: *Iron and Steel Manufacture*, 1868, Plate 29).
heat available in the chequers for transfer to the combustion air depended on the temperature and the volume of the exhaust gases and the latter varied markedly during the working of a heat. The maximum flow occurred during melting, while a more restricted flow was encountered when the damper was lowered to produce a mildly reducing atmosphere at the end of the heat. Gas fired puddling furnaces were installed, however, at several works. Nettlefold and Company operated 30 of these furnaces at their Wellingborough plant until ironmaking ceased there when the company moved the production to Newport in South Wales. A few regenerative furnaces were also built with two hearths, one of which was melting a charge whilst the other was in use for puddling a heat. Three furnaces of this type were reported to be in use in 1893 in Sheffield.32

There have been few tasks in an ironworks which have been as arduous as the work involved in the puddling of iron. The heat was less intense than when working on an open hearth furnace, but the puddler was exposed to the heat for much longer periods of time while manipulating the heavy, pasty mass of the charge to expose fresh surfaces and accelerate the rate of removal of carbon and other elements. Not surprisingly, there were frequent strikes by the workers in attempts to secure better pay and working conditions. Their case was assisted by the increasing shortage of people who were willing and physically capable to take on the task when the number of puddling furnaces in use increased rapidly during the 1860s and 1870s. Numerous attempts were made, therefore, to substitute mechanical devices for manual effort. An added impetus to achieve this objective came with the fight to reduce costs and retain the market for the product when the bulk steel-making processes had become established. Larger puddler’s balls of wrought iron were then required to produce items such as ship plate that could otherwise be made from one steel ingot. Between 1867 and 1876 a total of 389 patents were taken out describing mechanical devices that were intended to achieve these aims.12

One of the earliest devices took the form of a rotary furnace, which was erected at the Dowlais Iron Works. This comprised of an iron drum, mounted horizontally on bearings and connected through rotary seals to a fixed firebox and an exhaust stack. Problems arose during operation, for the pig iron coagulated into balls which simply rotated with the drum and did not expose fresh surfaces for oxidation. W. Menelaus, the works manager at Dowlais, countered this in 1865 by making the cross-section of the drum into an oval shape. The balls of iron did then drop and fracture, but the impacts fractured also the refractory lining. Only a poor quality iron could be produced from the furnace for, after extensive trials, ganister and some other siliceous materials were found to be the only refractories which could withstand the impacts, so sulphur and phosphorus could not be removed from the iron.

A similar furnace was constructed in 1870 at the West Hartlepool Rolling Mills, but wider interest was shown in a British patent issued in that year describing the mechanical process that had been developed in the USA by Samuel Danks.36 This also used a cylindrical furnace. It was constructed with stove plates that ran horizontally along the drum to hold the lining in place and to cool the outer layers. The lining was built up with pulverised iron ore, which was gradually sintered onto a
fused layer of iron ore and lime. The end opposite to the firebox could be swung to one side to allow access for the removal of the puddled ball by a crane. Consequently, it was claimed that charges of up to 300 kg could be worked successfully. A tap hole in the end wall provided a means for running off the slag containing most of the impurities that had been oxidised out of the iron before the start of the carbon boil, resulting in a purer iron cinder remaining in the puddled ball.

The Danks process seemed to be the answer to the problems that were troubling the British wrought iron manufacturers. At the instigation of Menelaus, the Iron and Steel Institute sent a three-man delegation to America to evaluate the process. The members were George James Snelus, James Lister and John Alcock Jones representing respectively the industry in South Wales, the Black Country and the North East Coast. In October 1871, they observed the processing of sample heats from four British works at the Danks factory in Cincinnati, Ohio. Their enthusiastic report to the Institute in the following January generated wide interest. The first Danks furnace in Britain became operational a few months later at the Teesside Ironworks and J. A. Jones was appointed managing director of the new Erimus Ironworks which was erected on Teesside to house six Danks furnaces. More than seventy of these furnaces had been built in Britain by the end of 1874, in the belief that they would allow production to be continued at lower cost than with the conventional furnaces during the recession which was then afflicting the industry. Serious problems were soon encountered from wear and mechanical breakdowns, however, and all the furnaces had been closed down within five years. This was just one of many nineteenth century inventions that was too far in advance of the available engineering technology. The British wrought iron trade had shrunk very markedly by the time the operating problems had been resolved.

2.3.4 Shingling and Rolling
The puddler’s balls, which were removed from the furnace at the end of the heat, were a conglomerate of iron and slag. Whilst still hot, the balls were transferred to a hammer to consolidate the metal and expel most of the slag by forging or shingling. Initially this was accomplished using a water-powered helve hammer, but steam powered hammers began to appear early in the nineteenth century. A vertical crocodile squeezer, with one fixed and one moving ribbed jaw was first used in 1805 and a horizontal rotary squeezer was developed a few decades later. The Nasmith steam hammer became available in 1842 and it then became possible to forge-weld two or more balls of wrought iron into one piece to make larger components.

It was difficult to produce a long bar under the hammer with a cross-section smaller than about 5 cm, but smaller cross-sections with uniform dimensions over the full length could be produced readily using a rolling mill with the grooved rolls which Cort had developed in 1783. Three of these rolling mills had been installed in South Wales and one was located at the Wortley Forge near Sheffield by 1790. Knowledge of the capabilities of the mills spread rapidly and, by the beginning of the nineteenth century, every malleable iron works had to have one.

Most of the slag was exuded from the mass in the first consolidation stage and fur-
ther quantities were squeezed out in each subsequent pass through the rolling mill until, with falling temperature, the slag became too viscous for further extrusion. Iron consolidated to this stage was sold as puddler's bar or muck bar. The mechanical properties of the iron were improved by piling. This involved a first stage deformation to produce slabs about 25 mm thick, 50–200 mm wide and up to 3 m in length. Each slab was then sheared into pieces 0.5–0.8 m in length. Five or six lengths were stacked together in a pile and bound together with wire. After reheating in a reverberatory type of furnace, the pile was again forged or rolled down to size. Welding of the stack of plates into a solid mass during hot deformation was aided by the preferential oxidation of the phosphorus dissolved in the iron to form a liquid FeO–P₂O₅ phase covering the surfaces. This was squeezed out as the plates were welded together. The re-rolled product was sold as merchant or crown bar. A repetition of the piling and rolling procedure gave a further improvement in properties and the product was then sold as Best bar. There was little gain from repeating the piling more than three times (making Best Best iron), for with continued working the layered ferrite-pearlite structure became too disseminated and the toughness of the material deteriorated.

By midcentury it had become common practice to use a higher-quality malleable iron for the top and/or the bottom layer of the final piling in order to confer enhanced surface properties, such as wear resistance on the flange of railway rails or toughness in armour plate. For less demanding applications the pile was sometimes constructed from small pieces of malleable iron scrap sandwiched between two outer layers of new puddled metal.

Wrought iron produced by the Low Moor Iron Company in Yorkshire was generally acknowledged as the best quality that was made in Britain. The highest grades sold by the company commanded a premium that was sometimes twice the price charged for the same grades produced elsewhere.

2.3.5 Output and Location
Estimates of wrought iron production during the first half of the nineteenth century show even greater variations between the compilations than those for the production of pig iron. This is possibly because wrought iron manufacture was distributed over a large number of sites, many of which operated only a few furnaces with low outputs. Most of the estimates for production in the earlier years were based on the rather dubious assumption that about 10% of the output from the blast furnaces was used for the manufacture of iron castings and the remainder was converted into malleable iron. At times, and particularly during periods of war, the foundries consumed significantly larger amounts of blast furnace metal. More reliable information is available for the later decades, when the British Iron Trades Association began to collate output data for the industry. Estimates of the annual production for various periods during the century are summarised in Table 4.

The output increased roughly ten fold between 1812 and 1840 with only a four fold increase, from 94 to 377, in the number of puddling furnaces, reflecting the rising demand for wrought iron and the introduction of the more efficient wet puddling method. Throughout this period, the selling price of muck bar averaged £10
Table 4  Wrought iron production: source of statistics. Refs. 9, 12, and 39 and Statistics – United Kingdom: J. Iron Steel Inst., annual volumes from 1869–1900

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<th>Year</th>
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per ton. Output declined during the early 1840s, but recovered when the railway boom created a demand for wrought iron rails. The cost of pig iron fell in 1840 and wrought iron prices followed suit, falling to just over £5 per ton for muck bar in 1843. After a temporary recovery, the prices descended to the same level again in 1851. Production increased rapidly during the Crimean war and again during the American civil war, to reach a peak output of about 3 million tons in 1875. Output then fell rapidly under the impact of the recession and with the erosion of the market for malleable iron by steel made in the new bulk steelmaking processes. There was some recovery in demand in 1882 and another small recovery in 1889 but, thereafter, the output of puddled iron decreased steadily and fell to a level at the end of the century below the output that had been achieved in 1840. The selling price recovered temporarily to exceed £10 per ton from 1872 to 1874, but otherwise varied between £6 and £7 per ton throughout the last half of the century.

After the expiry of Cart’s patent, the first commercial development of the puddling process took place in South Wales and twenty-seven furnaces had been brought into use by 1812, mainly in the Merthyr Tydfil area which produced one fifth of the British output in that year. Shropshire was not far behind with twenty-five furnaces and thirty-seven furnaces were distributed in other parts of England, mainly in the Midlands and in South Yorkshire. Scottish pig iron was not considered to be suitable for puddling and only five furnaces, all at the Carron works, had been erected in Scotland by this time.²

Reflecting the changes in the location of the blast furnaces, the industry in Shropshire grew at a less rapid rate than in most other locations. In 1839, there were 377 puddling furnaces in use in Britain, of which 113 were located in the Black Country. By 1850 this district produced annually 364,000 tons of malleable iron. In
contrast, the twenty-nine furnaces in use in Shropshire produced only 81,000 tons of metal. The wrought iron industry had started to grow in Scotland by that time, following the start of the hot blast practice for blast furnaces, and fifty-four furnaces produced about 200,000 tons of iron. But these performances were dwarfed by the output from South Wales, where 122 furnaces produced 454,000 tons of wrought iron. A major cause of the rapid growth of Welsh production was the strong demand for railway rails, which had become a local speciality. The Dowlais works had begun to produce rails for the horse-drawn tramways in the 1820s and installed a new rolling mill, dedicated to the production of rails, in the next decade. Other districts, including South Yorkshire and Derbyshire, soon joined in the rail trade but South Wales continued as the major production centre, aided by a strong export market for its products.

Only five puddling furnaces had been installed in the North East coastal region by 1840 but, following the development of the local ironmaking practice based on the Cleveland iron ore deposits, a wrought iron industry began to grow rapidly in the district. The number of puddling furnaces in the region increased to 300 in 1850, 646 in 1863 and 1467 in 1869. In the latter year a total of 6234 furnaces were in use in Britain. The largest concentration was in the Black Country, with 2155 furnaces, and Wales had declined to second place in terms of output. Two years later the North East region had moved into second place with 1862 furnaces, 120 of which were concentrated on one site at Sir Bernard Samuelson’s Britannia works at Middlesbrough.

Bessemer steel was beginning to emerge at this time as a serious competitor for the applications traditionally supplied by malleable iron. The selling price of wrought iron rails was £10 per ton less than for steel rails in 1864, but the price advantage had disappeared by 1870 (Ref. 18) and steel then rapidly emerged as the preferred rail material.

The boom conditions in the early 1870s encouraged growth in the malleable iron industry and the number of furnaces rose to a peak of 7575 in 1875. But only 5183 furnaces remained in use by 1881, when the main production centres were the North East region (669,189 tons) and South Staffordshire (580,000 tons). The demand for wrought iron ship plate ensured the survival of the malleable iron industry to the end of the century in the North East Coast region and the Black Country continued to supply about 30% of the total output from over 1000 furnaces. South Wales production was then limited almost entirely to the production of tin plate sheets. The number of furnaces at the Dowlais works had fallen from a peak of 255 to only 15 by 1897. Steel had displaced iron as the preferred material for almost all engineering applications.

3. STEELMAKING PROCESSES

In contrast to the rapid growth in the production of cast and wrought iron in Britain during the first sixty years of the nineteenth century, the manufacture of steel continued on a very small scale during this period. An indication of the perceived
importance of steel, prior to the development of the Bessemer and open hearth processes, is given by examination of the textbook written by John Percy entitled *Metallurgy Iron and Steel* which was published in 1864 (Ref. 16). A total of 564 pages were devoted to accounts of the production, fabrication and properties of cast and wrought iron. The descriptions of the production and properties of steel merited only ninety-six pages and this covered mainly the cementation and crucible processes. Small quantities of puddled steel were being marketed at that time and almost as much text was devoted to a description of this transient technique as was given to the Bessemer process, which had been in commercial operation for over four years when the book was written. Within a decade the scene had changed completely. Britain had become the major steel production country in the world and retained that position until some time after other countries had entered the market for bulk steel production.

3.1 Cementation

The cementation process was well established by the start of the nineteenth century, but there are few reliable estimates for the output. One assessment\(^3\) indicated that sixteen furnaces installed in South Yorkshire, mostly in Sheffield, were producing over 2000 tons of blister steel per annum in the closing years of the eighteenth century. This implies an average output of about 125 tons per furnace. South Yorkshire was beginning to displace the Newcastle district as the main centre for steel production at this time. Almost half of the British output of blister steel was made there, so probably not more than forty cementation furnaces were available in the whole of Britain at the dawn of the nineteenth century.

By 1837, the total production had risen to about 22,000 tons from ninety-seven furnaces. Growth thereafter was more rapid, reaching outputs of 40,000 tons from 160 kilns in 1853 and 78,000 tons from over 200 furnaces by 1863.\(^4\) The main location for the industry outside South Yorkshire was in the Black Country, although some furnaces were still in use in the vicinity of Newcastle-upon-Tyne and in Lancashire. This marked the peak of blister steel production. The output began to decline after 1875, but over 90 kilns with an annual production capacity of over 30,000 tons were still in use in the Sheffield area in the closing years of the century. Daniel Doncaster and Sons Ltd made the last heat in 1951, and the kiln in which it was made is preserved on the site of the works at Hoyle Street in Sheffield.

The two-chamber furnace surmounted by a conical chimney had become the standard design by 1800 and this pattern did not change. The capacity initially averaged 7.5–10 tons per heat, but some kilns could accommodate a charge of 20 tons by the 1830s. Twenty years later, the largest furnaces could accept a charge of 20 tons in each chamber and produce about 250 tons of blister steel per annum, but there was no further significant increase in the capacity. Coal fires heated the charge and the coal consumption per ton of product decreased as the quantity of metal which could be carburised in each heat was increased. By midcentury the fuel consumption had decreased to 1 ton of hard coal for each ton of blister steel produced.\(^9\)
Although the selling price of British-made wrought iron had fallen below the cost of iron imported from Sweden and Russia by the early 1800s, the imported material, which was made from charcoal pig iron, was preferred for the majority of applications. No more than 20% of blister steel was made from home-produced wrought iron during the first half of the century. This proportion had increased to about 40% by 1860, but Swedish Dannemora iron was still preferred as the base stock for the more demanding applications and particularly for the production of a carburised melting base for use in crucible steelmaking. Charcoal continued to be the preferred carburising medium, since the probability of sulphur transfer to the metal when converting with coke was now well known. It had also become recognised that the carbon was transferred to the iron by the dissociation of carbon monoxide, coupled with the regeneration of the gas by the Boudouard reaction. An 1825 patent described carburising with a hydrocarbon gas in the absence of solid carbon. The expertise was not available, however, to exclude air completely from the hot reaction zone and so avoid oxidation of the gas and the commercial application of the concept was delayed for over a century.

The metal was usually carburised at about 1050°C. With improvements to the design of the heating system, it became normal practice to heat the charge to the reaction temperature in less than 24 hours. The soaking time at temperature depended on the grade of blister steel and the depth of carburising required and varied from five days for the less demanding applications to nine days for crucible melting stock. The kiln was then cooled slowly over a period of five to seven days to reduce the risk of cracking the carburising chest.

With the exception of 'Steel through' heats, the carbon content of the steel varied from the surface to the centre of the metal. The surface was often severely distorted by blisters, so it was usually forged or rolled to improve the usability and the appearance. Many different and, in retrospect, sometimes intriguing explanations were advanced to explain the cause of the blister formation. Percy eventually postulated that carbon diffusing through the iron generated bubbles of carbon monoxide by reaction with iron oxides entrapped in the wrought iron stock. He then showed that no blisters were formed on malleable iron that had been remelted to separate the residual particles of slag before carburising.

The hot worked metal was suitable for immediate use to make artifacts such as carriage springs and the cheaper grades of cutlery. For more demanding applications the bars were piled and reheated, prior to forging or rolling, in a manner similar to the production of wrought iron. The thickness of the alternate layers of carburised and unaltered metal was greatly reduced by this treatment and the product was designated as 'Shear Steel'. Double Shear Steel was obtained by repeating the piling and hot working operations. A 'Steel through' heat with a carbon content of over 1.2% could only be forged with great care and usually required at least one reheating before the required shape and size was attained.

Some carbon was lost on each occasion when the metal was reheated for mechanical working. During carburising, therefore, the aimed mean carbon content of the bars was fixed with regard to the number and the duration of the reheats to
which the bars would be subsequently exposed. The carbon content was varied also according to the intended applications of the steel. Each manufacturer provided his own classification of the grades produced. In the majority of cases, the grade was assessed from the appearance of a freshly fractured surface and a skilled operator could estimate the carbon content by this means to within ±0.05%. Typical classifications were:

<table>
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<th>Temper</th>
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</tr>
<tr>
<td>2</td>
<td>0.75–0.85</td>
</tr>
<tr>
<td>3</td>
<td>0.9–1.0</td>
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<tr>
<td>4</td>
<td>1.05–1.15</td>
</tr>
<tr>
<td>5</td>
<td>1.2–1.35</td>
</tr>
<tr>
<td>6</td>
<td>1.4–1.6</td>
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</tbody>
</table>

Spring Steel
Cutlery Steel
Shear Steel
Double Sheer Steel
Steel through Heat
Melting Stock

The cost of conversion from wrought iron to blister steel increased slightly from grades 1 to 6, but was usually in the range from £1.00 to £1.50 per ton. Costs fluctuated also with the rise and fall in demand, but showed no overall trend with time. A progressive increase in the cost of charcoal was compensated by a fall in both the cost and the quantity of coal used for heating. The small variations in the cost of the malleable iron bars had very little effect on the selling price. The overall result was that with improvements in the scale of operation, coupled with the negligible rate of inflation, the selling price for spring steel bars remained in the range from £25 to £30 per ton and shear steel sold for £45 to £60 per ton for most of the century.

3.2 Crucible Steelmaking

In 1800, the Huntsman’s crucible steel process was the only means used for the production of liquid or cast steel. Seventy years later the output from the process had been dwarfed by the production from the new methods of bulk steel production, but crucible steelmaking remained throughout the century as the accepted method for the production of the best quality steels for use in the most demanding applications. In the closing decades, however, the new processes were encroaching on the lower end of the special steels market and the range of applications for which crucible steel was regarded as essential was correspondingly restricted. Improvements in the mode of operation, stability in the cost of the raw materials and, in later years, the increasing competition from other processes resulted in an almost constant selling price for the steel. The highest grades commanded a price of £50–£60 per ton whilst the lowest cast steel grades usually sold for at least £40 per ton.

The Huntsman process was developed initially in the vicinity of Sheffield and the subsequent growth occurred mainly in that area, where the local resources met almost all the raw material requirements. The ganister deposits found nearby at the village of Stannington and in the Wharncliffe woods provided the major con-
stituent of the clay mixture required for crucible manufacture and abundant supplies of good coking coal were obtained from mines located only a few miles from the town. A few crucible works were built during the century in other parts of the country, notably in the North East region and in the Black Country, but it appears that 90–95% of crucible steel was made in Sheffield and in the immediate vicinity.

The charge for a melt rarely weighed more than 9 kg in 1800 and a melting hole could process only three or four heats in a 12 hour working day, so each hole could produce about 16–18 tons of cast steel per annum. A typical melting shop containing five melting holes had an annual capacity of about 80 tons. Thirty years later, larger melting holes were in use which could accommodate two crucibles simultaneously, and improvements in crucible manufacture enabled some steelmakers to melt charges up to 18 kg in weight. Five-hole crucible pits utilising these developments then had an annual capacity of about 320 tons. A small scythe works containing a melting shop of this type is preserved as a working museum at the Abbeydale Industrial Hamlet in Sheffield.

The cast steel industry in Sheffield began to expand more rapidly after 1819, when the extension of the Rotherham canal to the eastern outskirts of the town provided a water-born transport route for iron imported from Sweden and Russia via the Humber ports to the industrial sites. This coincided with a growth in the demand for cast steel for use in railway rolling stock and for equipment in the new factories. The arrival of the first railway line through Sheffield in 1837 stimulated a further period of rapid growth. Initially the expansion was accommodated by the construction of larger melting shops with more crucible holes at the original works located within the town. Probably the largest of these was a new building which was opened at the West Street works of Sanderson Brothers and provided fifty-three double and thirty single melting holes.

The available sites within the town were soon filled and the locus for further development moved to the proximity of the canal and the railway, extending from the eastern perimeter of the town towards Rotherham. The first three works in this region were erected close to the original Huntsman works, shortly after the canal was opened. One of these, built by William Jessop and Sons, grew rapidly to become for a time the largest producer of crucible steel. The first of a new generation of larger works, which started initially with crucible melting but developed ultimately into a bulk steel producer using the Bessemer and open hearth processes, was opened in 1845 by Charles Cammell. A melting shop containing forty crucible holes was built on an adjacent site at John Brown’s Atlas and Spring Steel Works and additional holes were added during the next three years. Thomas Firth and Sons opened the Norfolk Works with eighty melting holes in 1851, but the building of the largest melting shop, which was designed to accommodate 340 holes, was started in 1863 at the River Don plant of Naylor Vickers and Company. The construction and enlargement of crucible melting shops in and around Sheffield continued into the 1890s.

The capacity of the crucibles continued to increase and 25–30 kg charges were commonly processed by midcentury, increasing on special occasions to about 45
kg. Each crucible was normally used for three successive heats, but erosion at the slag line necessitated a reduced weight of charge in the subsequent heats. Thus, a crucible that was used initially to melt 22 kg might melt 20 kg in the second heat and only 14 kg in the final heat. Information concerning the annual output of crucible steel is very limited. This is not surprising for the first half of the century in view of the relatively small tonnages of steel that were produced by each melting shop. Systematic attempts to collect output data for steelmaking were only started in the 1860s. Statistical data for iron and steel production were compiled by the British Iron Trades Association and tabulated in each volume of the *Journal of the Iron and Steel Institute* from when it was first published in 1869. But negligible data about crucible steel output were given either in the tables or in the papers that were published in the journal. Information in occasional assessments and reports refer mainly to the performance of the Sheffield industry. There is clear evidence of a vast increase in both the number of melting holes and in the annual production during the three decades following the start of the industrialisation of the Sheffield-Rotherham valley. The number of steel works in the locality increased threefold, from 50–150, but the process reached its production peak in the 1870s. One assessment of the production during the last quarter of the century, based partially on the quantities of iron imported from Sweden, indicates that the industry contracted markedly during this period. This was a result of the simultaneous impacts of the trade depression, which persisted throughout most of this period, and the loss of some of the market for crucible steel to the products from the new bulk steelmaking processes.

3.2.1 The Crucible Charge

The crucible process resembled the modern high frequency air melting process in the sense that it was a simple melting and homogenisation procedure with no attempt to refine the metal. Apart from the method of heating, it differed mainly in the use of a lid placed on top of the crucible to minimise the pickup of oxygen and sulphur from the furnace atmosphere. A small amount of slag was usually formed as an additional barrier through additions of broken glass or other siliceous materials, although from time to time various 'potions' were recommended as additions to improve the quality of the metal. Some oxygen was invariably introduced, however, in the slag fibres contained within the recarburised wrought iron and as rust on the surface of the charge metal. This resulted in a small loss of carbon. The silicon content of the metal often increased by up to 0.1%, owing to the reduction of silica from the crucibles by carbon in the steel during the later stages of the heat. Apart from these small changes, the weight and composition of the charge components determined the composition of the steel produced in a melt.

In the early years of the nineteenth century and following the practice which had been established by Huntsman, the charge for most steel qualities was prepared from good quality carburised Swedish or Russian wrought iron. British iron of lower purity was only considered to be suitable for the production of the cheaper grades of cast steel and constituted about 10% of the total melting stock. The cost
of the imported iron was at least £25 per ton throughout most of the century and this largely determined the selling price of the cast steel. Many abortive attempts were made to use less expensive materials for the charge before successful alternative mixtures were adopted in the second half of the century. Jeans has described a variety of the patents that were issued on this topic.  

British patent 2447, issued in 1800 by David Mushet described ‘the fusion of (uncarburised) malleable iron or iron ore in crucibles mixed with a proper percentage of carbonaceous matter’. It proved impractical to implement the procedure at the time, for the maximum temperature that could be attained in the furnace was below the melting point of the malleable iron and the lowering of the melting point by the solid state diffusion of carbon into the iron was too slow.

Josiah Marshall Heath described the first successful modification to the charge (British patent 8021, 1839). He melted manganese ore with coal tar to produce a ‘carburet of manganese’ (Mn₃C) and up to 3% of this alloy was incorporated in the crucible charge. It is apparent that the action of the compound on the melt was not understood, for a subsequent patent proposed the direct addition to the charge of tablets of manganese oxide mixed with tar. The carbide addition would remove any residual oxygen from the melt and, more significantly, precipitates of MnS would replace the grain boundary films of FeS. Together with the development of wet puddling, which removed a large part of the phosphorus from the pig iron, the addition of the manganese carbide made possible a greater use of British blister steel and the proportion incorporated in the total melting stock crept up to about 20% by midcentury.

William Vickers, from the Naylor Vickers Company, also devised a modified charge (British Patent 8129, 1839), which comprised pieces of white cast iron and wrought iron turnings, together with a small amount of manganese oxide and charcoal. The procedure overcame the problem with the implementation of Mushet’s proposal, for the furnace was heated to a much higher temperature than the fusion range for cast iron and the wrought iron turnings melted readily in the resultant metal pool. The major obstacle that impeded the adoption of this charge mixture was the difficulty encountered in the procurement of a supply of cast iron with low sulphur and phosphorus contents. Pig iron from charcoal blast furnaces was the preferred choice, but the major source at that time was from Scandinavia. The Swedish Jernkontoret had prohibited the export of pig iron, preferring the higher profits that could be obtained from the sale of wrought iron, so the Vickers patent could not readily be adopted. The rapid growth in the demand for wrought iron by midcentury, however, resulted in extensive deforestation in Sweden and a shortage of charcoal. The export ban on pig iron was eventually lifted in 1854 and crucible melters then rapidly adopted the mixture devised by Vickers. Since the carbon required in the melt was supplied in the pig iron it was no longer necessary to carburise the wrought iron used in the charge. When the River Don Works was opened in 1863 with its large battery of melting holes it contained no cementation furnaces.

From about 1870, manganese was usually added to the charge in the form of
spiegeleisen. It was normal practice to include cast steel scrap metal in the charge for the production of the cheaper grades of crucible steel. Towards the end of the century and in an effort to retain the market for those grades in the face of competition from Bessemer and open hearth furnace steel, some manufacturers started to use almost any available steel scrap to replace the wrought iron turnings.

3.2.2 Gas Firing
Charles William Siemens and his brother, Frederick, took out the first patent for a regenerative furnace in 1857 and the gas producer was patented four years later. Initially the principle was applied to the manufacture of glass, but a decade later he began to explore designs for regenerative furnaces which could be used for crucible steel melting. In the form that was eventually adopted (Fig. 6) a double row of crucibles was set on an elongated hearth. The crucibles were inserted and removed through lids in the furnace roof. Ports provided for the entry of preheated air and gas and for the exhaust gas to pass to the chequers, in similar manner to the form that was later adopted for open hearth melting. The direction of the gas and air flow was reversed at 20 minute intervals. The early furnaces of this type accommodated twenty-four crucibles, but larger furnaces were soon developed.

A higher temperature than was normally achieved in a traditional crucible melting hole was readily attained in the regenerative furnace, so the charge comprising wrought iron or iron ore and carbonaceous matter as originally proposed by Mushet could now be melted. Problems were encountered, however, when this was first attempted owing to the partial fusion and slumping of the crucibles. The difficulty was partially averted by the use of plumbago crucibles, which had been developed in the USA but, in the absence of reliable equipment for the measurement of the furnace temperature, considerable skill was required to achieve the required temperature without overheating the crucibles.

Fig. 6  Siemen's regenerative crucible furnace J. Iron Steel Inst. 1884 (2), Plate XXIV Fig 5.
Although the majority of crucible steelmakers continued to use coke-fired melting holes, several companies adopted the regenerative principle. One of the first applications was at the River Don Works, which was then being built. Construction of the conventional furnaces was halted and a battery of regenerative furnaces capable of heating 200 crucibles was erected. Seven companies were operating Siemens crucible furnaces by 1880 to hold a total of 534 crucibles with an annual melting capacity of about 20,000 tons. One of the major advantages obtained with this form of heating was the saving in energy. The fuel consumption per ton of cast steel fell from an average of 4 tons of high grade coal in the conventional furnace to only about 2 tons of cheaper coal with the Siemens furnace.

Huntsman's crucible process played an important role for over 200 years in the production of tool steels and other high quality grades, but the market was steadily eroded with the introduction of electric steelmaking and vacuum melting methods. The process was finally confined to history when the last British heat was teemed in 1968. It is commemorated, however, by a freestanding sculpture depicting a melter and his team pouring metal from a crucible into a mould. This is mounted in the centre of the Meadow Hall Shopping Centre in Sheffield, on a site which had been occupied by a steel works when the Sheffield–Rotherham valley was industrialised.

3.3 Puddled Steel

During the 1830s it was recognised that the principle difference between wrought iron and steel was the carbon content of the metal. This stimulated trials, which were conducted mainly on the continent, to modify the puddling process and halt the oxidising reactions before the carbon content had fallen to a very low level. A. Lohage and G. Braemme, working in Germany eventually achieved success with this approach in 1849. Ewald Riepe lodged a British patent application on their behalf in the following year and because of this action the technique is sometimes erroneously described in the English literature as Riepe's process.

In comparison to the conventional wet puddling procedure, the modified practice differed mainly in the addition of manganese oxide, mixed with common salt and dry clay, to lower the fusion point of the slag and allow the process to be operated at a lower temperature. The manganese oxide addition also replaced part of the iron oxide added as an oxidant. In the early applications of the technique, the aim was to control the temperature of the furnace so that the metal became a semisolid mass when the carbon content had been lowered to the required level. The control was poor, however, for no reliable method was available for the measurement of the furnace temperature. Although a fluid slag could be maintained by the additions of manganese oxide, large amounts of slag became entrapped in the puddled balls and this was only partially expelled during the subsequent forging and rolling operations. A heterogeneous mass remained after the mechanical working, differing from wrought iron only in the carbon content.

In later modifications of the process, the ratio of MnO to FeO was increased in
the oxidant additions. The furnace was heated to the temperature normally used for the production of malleable iron, but the damper was partially lowered to provide a smoky atmosphere, which was less strongly oxidising, when the required temperature was reached. The carbon boil then subsided as the oxygen supply was exhausted and sometimes an addition of spiegeleisen was made to kill the bath. Time was then allowed for the metal and slag to separate in the quiescent bath before solidification started, so the puddled steel contained less slag and was more homogeneous after mechanical working.

Hematite pig iron was the preferred melting stock, but a wide range of pig iron compositions could be processed. In comparison to the acid Bessemer and open hearth processes, one of the arguments advanced in favour of puddled steel production in later years was the ability to transfer most of the phosphorus and some of the sulphur from the pig iron into the slag, in similar manner to the composition change that occurred in the production of malleable iron.

The Riepe patent was issued in 1850 (British Patent 12950) and the Low Moor Iron Company took out the first license in the following year. Within the next few years licenses were also acquired by the Mersey Steel and Iron Company and by the Ebbw Vale works. In the latter case a blend of pig irons had to be used, for the majority of Welsh pig iron supplies had too high a sulphur content. By 1859 the Mersey Company was selling puddled steel at £21–£23 per ton for a wide range of applications including ship plate, rivets, chains, girders, piston rods and springs.

Faced with a loss of market, some of the crucible steelmakers built new furnaces to produce puddled steel. Three of the larger Sheffield firms were involved in this venture. Thos. Firth and Sons built a works containing eighteen puddling furnaces at Whittington in North Derbyshire. John Brown and Company started to produce ship plate and armour plate in puddled steel during 1858 and three years later seventy-two puddling furnaces were in use at the Atlas works. Charles Cammell and Company installed sixty furnaces at the Cyclops works. Elsewhere, the John Gjers Company started production in 1868 at Middlesbrough and John Kitson installed furnaces in 1876 at the Monkbridge works.

Puddled steel was markedly stronger than wrought iron. The tensile strength of the steel was usually in the range from 550–850 MN m\(^{-2}\), compared with about 380 MN m\(^{-2}\) for wrought iron. Despite the heterogeneity and poor toughness, the higher strength helped to develop a demand for low cost steel and the market flourished for a time. But production of puddled steel had practically ceased by the late 1880s as the basic steelmaking processes, which could produce a more homogeneous steel at still lower cost, came into full production.

One of the major problems, which persisted throughout the years of operation of the puddled steel process, was the lack of a precise control over the stage at which the puddling operation should cease in order to produce a steel with a chosen carbon content. When the process was first developed it required a minimum of 12 hours for the analytical determination of the carbon content of a sample of steel. The analysis could be completed much more rapidly in the later years and with an accuracy of ±0.05%, but few chemists were actually
employed in the works. As late as 1884, vague statements appeared in the press, such as

puddled steel is precisely the same as bar iron except that the process of puddling is stopped when rather more than half the carbon has been removed from the pig iron. It is usual to call all puddled bars which cannot be hardened in water bar iron and all those which can puddled steel, this dividing line falls somewhere near a mixture containing 0.5% carbon.47

3.4 The Bessemer Converter Process

Henry Bessemer was a self-educated engineer inventor who had patented a long list of inventions before he started an investigation that culminated in the development of the first bulk liquid steel production process. His autobiography provides details of his many achievements48 and an account has been given of the worldwide development of his converter process.49

His interest in ferrous metal production arose during the Crimean war, which started in April 1854, when he set out to improve the trajectory of artillery shells, which frequently missed their targets. He proposed the replacement of the traditional round shot with elongated projectiles containing longitudinal channels extending from the rear face and terminating in tangential vents. Gases released by detonation in the gun barrel would thus impart a rotary motion to the shell and improve the accuracy of the flight. The British War Office was not interested. With the aid of finance from the future Emperor Napoleon III of France, the concept was soon proven and the shell design perfected. But it was found that the cast iron gun barrels in use then were not strong enough to withstand the stress imposed during the firing of the larger projectiles.

Although he had received no metallurgical training or experience, Bessemer built a small reverberatory furnace in the works that he had erected to produce ‘gold’ powder and paint in the grounds of his home at Baxter House in St Pancras. He then embarked on a series of experiments aimed at the production of a stronger and tougher malleable iron. There was no reference to steelmaking in the initial program. In what was to prove a very significant modification of the conventional reverberatory furnace, additional air was blown through perforations in the fire bridge to accelerate the combustion of the gases and raise the furnace temperature. During the course of one experiment, Bessemer noticed that two lumps of pig iron, which had inadvertently been placed on the fire bridge, had not melted with the rest of the charge. Closer inspection revealed that they were merely shells of decarburised iron. He realised that the hot air blast had oxidised most of the impurities from the iron and that the heat generated by the oxidation reactions had been sufficient to melt almost all of the iron. This observation resulted in a change in the direction of his experiments, with a new objective of refining a bath of molten pig iron without the need for any extraneous heat supply.
3.4.1 Development of the Converter

The first small-scale experiments in the new series were performed using a conventional design of crucible furnace. A charge of 3–4 kg of pig iron was melted in a refractory crucible. A clay tube was then inserted through the crucible lid into the melt and a blast of air was blown down the tube to oxidise the impurities. No iron oxides were added, but a malleable iron was produced. Bessemer has provided a detailed account of the subsequent evolution of the design of the converter.\(^5\)

Realising that with small melts the rate of heat loss was equal to, or greater than, the rate of heat generation by the oxidising reactions, he built a larger fixed vessel to refine a charge of about 350 kg of molten iron. This furnace was 1.5 m high with a 0.9 m internal diameter, with five tuyeres of 10 mm diameter inserted through the sidewall about 50 mm above the bottom plate. The process worked satisfactorily and the refined metal was sufficiently fluid to allow it to be tapped from the furnace and teemed into an ingot mould.

Bessemer's seminal paper entitled "The manufacture of iron and steel without fuel", in which he gave an account of the first successful attempts to refine pig iron in a fixed converter, was presented on 11 August 1856 at the Cheltenham meeting of the British Association. He described also the design and operation of a casting pit. Hydraulically operated rams inserted in the base of the moulds were to be used to eject the ingots before solidification was complete and facilitate the transfer of the ingots whilst still hot to the rolling mill to avoid the need for reheating. The paper had a rather sceptical reception from the ferrous industry so in 1856 two ingots of 250 mm cross-section were cast at Baxter House and were rolled satisfactorily into rails at the Dowlais works in South Wales. Forty years later the analysis of a sample from one of the rails was given as\(^{26}\) 0.08% C, 0.162% S, 0.428% P with only trace amounts of Si, Mn and As.

Following the successful production of the rolled metal, licenses for the operation of the converter process were taken out by the Dowlais Company and also by the Butterley Company in Derbyshire, Messrs Galloway and Company, Manchester and the Govan works in Glasgow. Disaster soon struck, however. Metal refined from local pig iron at the Dowlais works teemed satisfactorily but disintegrated when subjected to hot deformation. Analysis, again completed forty years later, showed that the Dowlais refined metal contained 0.06% C, 0.01% Si, 0.276% S, 1.930% P and no manganese. The other licensees all encountered similar problems and Bessemer eventually had to rescind the licenses.

Several years elapsed before it was proven that the phosphorus content of the steel was the primary cause of the poor results obtained at Dowlais and elsewhere. Meanwhile Bessemer resumed his experiments at Baxter House and encountered no major difficulties with processing the charges which he prepared from imported Swedish pig iron. Steels with a wide range of carbon contents, similar in composition (judged from the fracture appearance) to those produced by crucible melting were made by halting the blow before the carbon flame dropped. The molten metal was then poured into water to produce metal shot and mixtures of the shot produced in different heats were remelted in crucibles to produce steel with the
required carbon content. In works trials, the product proved to be indistinguishable from crucible steel.51

The steelmakers were well aware of the earlier problems and, despite the success of the works trials, Bessemer was unable to find any company willing to take out a new license, so he decided to open his own factory. The Bessemer Steel Works was built in the recently developed industrial zone between Sheffield and Rotherham and the first cast of steel was made there on the 18 June 1859. Initially the works produced tool steel by the water quenching and crucible remelting procedure, which could be sold profitably at up to £20 per ton below the price of the equivalent grades of crucible steel. But it proved to be even more profitable to produce a homogeneous mild steel and this soon became the principle product of the works.

By this stage of the development, Bessemer had made several changes to the shape and the capacity of the converter and some of these are illustrated in Fig. 7. A serious drawback with the fixed vessel was the necessity to maintain the air blast continuously from when the molten charge was poured in until the refined metal had been drained completely from the vessel through a tap hole. Otherwise, there was a risk that the steel would solidify in the tuyeres. A design had been patented for a tilting spherical converter in 1855 (Ref. 50), but this was never built. The first tilting converter with a cylindrical shape was built at the new Sheffield works. The vessel had only one large tuyere mounted through the base and it was thought that

Fig. 7 Early Bessemer converter designs (J. Iron Steel Inst. 1886, (2), Plate XVI).
metal might be ejected through the concentric mouth of the vessel, so a spherical chamber was attached to the mouth. In this form the vessel could be tilted far enough to tap the metal through the mouth into the ladle, but the tuyere was not raised above the metal surface until the converter had been partially emptied. The design was soon modified into a form that was very similar in shape to the converters in use at the end of the century, with multiple tuyeres inserted through the bottom plate and an eccentric nose. This allowed sufficient rotation of the vessel to bring the tuyeres above the surface of the metal at the end of the blow. The first converter of this type, with a charge capacity of 1700 kg, was installed in the Bessemer works before the end of 1859. Within one year vessels of this shape were in use that could accommodate a 4 ton charge.

The early converters were lined with fire clay or silica bricks, but rammed ganister linings were in use by the early 1860s. The evolution of the converter and ancillary equipment was described in thirteen patents that Bessemer had taken out before his Sheffield works started production. A further sixteen patents followed during the next twelve years. One of these described the construction of a removable bottom section to facilitate replacement of the tuyeres, but this practice was not in general use until a decade later, following development of the idea in the USA.

During the early years of Bessemer steelmaking most melting shops contained two converters, mounted on opposite sides of a circular casting pit (Fig. 8). A crane mounted on a central pillar was used to transfer a ladle containing the molten charge from a cupola to the converter. After the completion of the blow it moved a bottom-pouring ladle to the vessel for filling and then rotated to bring it into position for teeming into the ingot moulds which were located around the periphery of the pit. The two-converter arrangement allowed continuous operation of the melting shop while each of the vessels was relined in turn. As the capacity of the converters was increased, however, and larger numbers of converters were installed in one melting shop the two-vessel layout was gradually replaced by a linear arrangement, with the converters mounted on a stage above the casting pit. This mode of operation became standard after the adoption of the removable bottom plate allowed rapid replacement of the tuyeres, for each converter was then in operation for a much longer period before it was removed for a complete reline.

In the first decade of the operation of the process, the ingots were usually top poured in a scaled-up version of the practice that Bessemer had described in the Cheltenham paper. As the capacity of the converters increased, however, problems began to be encountered owing to inadequate superheat in the metal, which resulted in excessive shell formation when several ingots were teemed in succession from one heat. The problem was eventually avoided by adoption of the method devised by B. D. Healey (British Patent 11873, 1873) for the uphill teeming of a cluster of ingots fed from a central runner.

3.4.2 The Hot Metal Charge
Fortuitously as it transpired, Bessemer had used a pig iron purchased from the Blaenavon works for his first experiments. This could be refined in the converter to
produce a metal that was easily forged or rolled to shape. The first group of licensees quickly discovered that pig iron obtained from other sources in Wales and from various suppliers in Scotland and the English Midlands was not suitable for the charge. Bessemer then used Swedish charcoal iron for his continuing experiments in London and used the same supplies when commercial production was started at his Sheffield works. Methods for the chemical analysis of metals and ores were being developed at that time and it was soon shown that the grades of pig iron that could not be refined and forged satisfactorily contained too much phosphorus. The Blaenavon pig iron was made from a hematite iron ore with a low phosphorus content, but it was not produced in large quantities and could not satisfy the demand when the Sheffield works was established. West Cumberland was a major supplier of hematite pig iron and in 1862 Bessemer tested pig iron supplied by the Workington Iron Company. It was found to contain a high phosphorus content. Bessemer discovered that this contamination originated from the incorporation of puddling cinder as a flux in the blast furnace charge. On his recommendation, the cinder was replaced by local shale and thereafter Cumberland pig iron became the standard converter charge.

For maximum thermal efficiency, Bessemer initially intended that the molten pig iron should be transferred directly from the blast furnace into the converter, but
problems arose from the variability of the composition and the temperature of the metal tapped from the blast furnace. He recognised that the oxidation of the silicon in the metal was the main source of heat in the converter, with only a small contribution coming from the oxidation of carbon. To ensure a more or less constant level of fluidity of the metal produced from the small capacity converters that were used initially, it was essential to maintain a concentration of approximately 2% Si in the charge. This could not be guaranteed with a feed direct from the blast furnace. All the early melting shops, therefore, incorporated cupolas in which a suitable blend of cast irons could be melted to provide molten pig iron of the required composition. Increases in the converter capacity and in the control of the blast furnace eventually made direct charging a practical proposition. It was first applied in Britain in 1875 at the Barrow works and shortly afterwards at Dowlais and Ebbw Vale. But in 1879 it was noted that 'opinion still obtains in some quarters that the direct process is less under control and the resultant steel may therefore be less uniform'. A survey completed three years later revealed that sixteen of the twenty-eight Bessemer plants then in operation did not include blast furnaces on the site, but the output from those works was only one third of the total Bessemer steel production.

Residual opposition to the use of a direct feed was finally quelled by the interposition of a hot metal mixer between the blast furnace and the converter. The first British mixer, which was installed in 1890 at the Barrow works, was similar in shape to a very large Bessemer converter. Most of the other integrated iron and steel plants rapidly followed suit. The first mixers were inactive and were used solely for the chemical and thermal homogenisation of the metal tapped from two or more blast furnaces. An active mixer practice for the preconditioning and partial desulphurisation of the hot metal was introduced in the closing years of the century.

3.4.3 Bessemer Steel Works
Following the successful launch of his Sheffield works, Bessemer read a paper entitled 'On the manufacture of malleable iron and steel' at a meeting in May 1859 of the Institute of Civil Engineers. This revived interest in steelmaking in the converter. The first company to take up a license for the viable process was John Brown's, whose premises shared a common boundary with Bessemer's works. Brown installed a 4 ton capacity converter in 1860 and within a year he was marketing Bessemer steel at £22 per ton. Four years later, after supplies of low phosphorus Cumberland hematite pig iron became available and with the addition of more converters, the selling price had fallen to £17.50 per ton. This was less than half the price of the cheapest grade of crucible steel and the demand for the products rapidly overcame the remaining scepticism about the ability of the process to produce a sellable product. Charles Cammell took out the second license and nine licenses had been issued by the end of 1863. Based on the number and the capacity of the converters that had been installed, the gross annual capacity could not have exceeded 7000 tons by the end of that year. Most of this output was consumed in
the construction of the rapidly expanding railway network. Trials had demonstrated the vastly superior wear resistance of rails made from steel over those made from wrought iron and, despite the higher cost, rails became the major product of the Bessemer steel works.

The commercial success of the first group of new licensees encouraged a few more companies to adopt the process. Fifteen licenses had been issued by 1867 and sixty-three converters had been installed, as listed in Table 5. Seventeen of these vessels were located in four works in the Sheffield area. Twelve were located in South Lancashire and Cheshire in works that were heavily committed to the steel rail trade. The largest concentration of converters on one site was located at the newly established Barrow Hematite Steel Company, which grew rapidly to become for a time the largest steel works in the world. Elsewhere, two plants in South

Table 5  Location of early Bessemer Converters: source of data Refs. 9 and 39 and Statistics – United Kingdom: J. Iron Steel Inst., 1868, 1871.

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<td>Blaenavon Iron Co.</td>
<td>1878</td>
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Wales substituted converter steel for wrought iron in rail production, but only two other works in England and two in Scotland had adopted the converter process by that time. A small melting shop housing two 2.5 ton converters was also commissioned by Bessemer at Greenwich, on a site adjacent to the area now occupied by the Millennium Dome complex. He had hoped to establish the building of steel ships on the river Thames, but the site proved to be too remote both from the raw material supplies and from the customers for the products and the works did not achieve profitable operation. No new licenses were issued during the next four years, but the existing licensees installed an additional twenty converters. The annual output of converter steel had risen to 329,000 tons by 1871 (Table 6), which was roughly fifty times greater than the output for 1863.

Three new Bessemer works, which were built primarily to exploit the rail trade, began production in 1872 in the Sheffield area, increasing the total capacity for rail production in the region to over 250,000 tons. Most of this output was exported, mainly to the USA but also to countries that were developing railway networks in Europe and elsewhere. Unfortunately for the new entrants to the trade, the export sales collapsed, following a financial crisis in 1873 in the USA. The selling price for steel rails fell in consequence from a peak of £17.50 per ton in 1873 to £9.87 in 1874 and continued to fall to only £4.65 by 1879. Faced with increasing competition from the Bessemer steel works that were being opened in America, rail exports across the Atlantic were never restored to the level that had been reached in 1873. The fall in the selling price placed the works on inland sites at a disadvantage, relative to those which were close to the supplies of hematite pig iron and also close to the ports for

<table>
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<th>Basic</th>
<th>Total</th>
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shipment of the rails to overseas customers. John Brown and Company closed their rail mill in Sheffield. Charles Cammell transferred all rail production to their Bessemer plant at Dronfield in North Derbyshire, but within a decade the whole of this plant was transferred together with most of the workforce to combine with the Derwent Iron Works at Workington.

The decline in the rail trade did not halt the growth of Bessemer steel output, for these two companies led the diversification into the manufacture of other products including ship and armour plate, joist and girders, whilst continuing with the production of railway springs, tyres and axles. By 1878, just before the first basic-lined converters were built, a total of 111 converters, installed in twenty-five works, produced 818,525 tons of steel. This corresponded to a little over a seven fold increase in output in a decade. Approximately 75% of this production was rolled into rails. The output peaked in 1882, by which time South Wales had replaced Sheffield as the largest production district, then declined during the recession in the mid 1880s. The all-time peak output of acid Bessemer steel was reached in 1889. This was followed by a rapid decline as the acid open hearth process and, to a less extent, basic steelmaking began to make inroads into the market.

The growth of production in the two decades between 1869 and the peak year of 1889 was primarily a result of improvements in the efficiency of operation and only partially to the installation of additional plant. Thus, in 1869 one pair of converters in a typical two-converter circular arrangement averaged not more than five heats in a 12 hour shift. With the introduction of detachable bottoms for the converter and other improvements, this had risen to fifteen heats by 1881 (Ref. 4) and the number of blows per shift continued to increase. A few plant developments did occur, including the construction of a melting shop with two 6 ton converters by the Darlington Iron Company in 1880. Four 10 ton vessels were built at the Castle Works, Rogerstone in the following year, when Nettlefold and Chamberlain moved their manufacturing base to Cardiff. Four 10 ton converters were installed also at the Cyfarthfa works near Merthyr Tydfil in 1884.

These additions were more than matched by plant closures elsewhere. The Mersey Steel and Iron Company ceased trading in 1882. Some of the converters from this works were subsequently re-erected for basic steelmaking at the Staffordshire Steel and Ingot Iron Company at Bilston. The Tredegar works, which opened in 1882, had ceased production of Bessemer steel by 1892. The Weardale and Rymney works also stopped production at this time, followed shortly afterwards by the Darlington Company and the West Cumberland Company. Some converters in other works were relined with basic refractories to operate the Thomas process. Only forty-one acid lined vessels remained in use at the end of the century.

3.4.3 Control of the Process
The understanding of the chemical reactions that occurred within the converter and the ability to control the composition of the refined metal advanced only slowly as the century progressed. Before the tilting vessel was perfected, the need to continue
the blast until the refined metal had been completely discharged into the ladle frequently resulted in over oxidation of the heat. Robert Foster Mushet, working in collaboration with the Ebbw Vale Iron Company, found evidence of this in samples taken from some of the earliest heats blown in a converter. The Company took out patents (British Patents 2168, 2169 and 2170) in 1856 on his behalf, describing a method to rectify this defect by the addition of ‘a triple compound of iron, manganese and carbon to deoxidise the bath before teeming the metal into the mould’. Unfortunately for Mushet, following the cancellation of the original Bessemer licenses no interest was shown in the method. The Ebbw Vale Company did not renew the patents and they expired in 1859. When commercial production of steel started at the Bessemer works, Mushet received no royalties for devising an important step in the successful development of the converter process. With some justification, Bessemer could claim that manganese deoxidation was a standard procedure with the crucible steelmakers, but he voluntarily paid Mushet a pension for the rest of his life.\textsuperscript{48}

The progress of the reactions within a tilting converter was normally judged by the changes in the colour and the intensity of the flame which emerged from the mouth of the converter. The blow was halted when the flame dropped, charcoal pig iron was then added and the blow was resumed for a short time when attempts were being made to produce medium or high carbon steel. In all other melts spiegeleisen or ferro-manganese was added when the flame dropped and the blow was resumed for a few seconds before the converter was emptied. In later years, when the reaction mechanisms were better understood, manganese was added also to precipitate the sulphur as MnS when processing pig irons with unacceptably high sulphur contents.

Owing to the rapidity of the reactions, the determination of the exact moment when the converter should be turned down to produce a low carbon steel without over oxidation was a major problem. A metal sample could not be taken without turning-down the vessel and halting the blow. A serious loss of heat could occur from converters of small capacity if the blow remained suspended while the composition of the sample was assessed by either fracture appearance, magnetic susceptibility or ease of deformation. A significant step forward was made in 1862, therefore, when Professor Roscoe and William Bragg used a spectrometer at the Atlas works of John Brown to determine the end point of the heat by the analysis of the gases leaving the mouth of the converter.\textsuperscript{9} Blue and green lines, which appeared in the spectrum, were ascribed to manganese and carbon emissions and the progress of the heat was assessed from the variation in the intensity of these lines. A further advance was made a few years later when the off-gases were sampled and chemically analysed at various stages during the blow and the resultant data were correlated with the recorded changes in the spectrographic analysis.\textsuperscript{58} It was deduced from this work that silicon was oxidised preferentially from the metal in the early stages of the blow and carbon was oxidised to CO\textsubscript{2} when the metal temperature was low. Carbon lines appeared in the spectrum as the temperature of the melt increased. It was then assumed that carbon monoxide released at the metal
surface was ignited at the mouth of the vessel to produce the flame. The spectrographic analysis gave some help in determining the end point, but by the end of the century no better means had been found to replace the observation and judgement of the skilled melter for determining the end point of the blow.

Henry Bessemer died in 1898. His achievements had been honoured during his lifetime by many awards, including a knighthood and several medals and prizes. His memory is perpetuated by the many buildings, streets and other artifacts, here and overseas, which still bear his name.

3.5 Siemens Open Hearth Process

3.5.1 Early Developments

Charles William Siemens came to Britain in 1843 to sell an improved method of electroplating that he had developed with his brothers. He had received a scientific education and from theoretical principles embarked with his brother Frederick on an experimental programme which culminated in the invention of the regenerative furnace (British Patent 1320 dated 1857). This was one of over 100 patents taken out in his name, almost equalling the number taken out by Henry Bessemer.

Reference has been made earlier in this chapter to the application of the regenerative furnace for puddling and for crucible melting. Siemens recognised also the potential for its application in steelmaking by melting and then refining a charge in a reverberatory-type furnace, but the first attempts to accomplish this were made by other workers. Charles Attwood, the proprietor of the Weardale Bessemer Works, built a small silica lined furnace in 1862 to a design supplied by Siemens. It was used initially for crucible melting, but attempts were made also to melt a charge of white cast iron and malleable iron with the addition of glass cullet to form a protective slag. The process was thought to be worthy of protection by a patent, but the brick structure of the furnace could not withstand the long exposure to high temperatures and the heats had to be halted because the roof had collapsed into the bath, so the trials were abandoned.

The first commercial success was achieved using a similar approach under license in France by the Martin brothers, Pierre and Emile. Their British Patents (No. 2031, 1864 and No. 2137, 1865) described a procedure for melting pig iron on a silica hearth and adding scrap malleable iron, scrap steel or, preferably, balls of puddled iron and puddled steel to the molten bath. Blast furnace slag was added to form a cover. The first patent described the operation as a continuous process with half of the molten mass being tapped off before additional solids were charged. But there was inadequate control over the metal composition with this mode of operation and the later patent described a batch-type process. This was a simple melting operation, similar in metallurgical terms to crucible melting, in which the composition of the metal produced was controlled by varying the make-up of the charge and with no attempt at active refining. It became known as the Siemens-Martin or the pig and scrap process.

In a repetition of the negative attitude that Bessemer had encountered in the
development of the converter process, Siemens was unable to find a British steelmaker who was willing to collaborate with him in developing his process. This was mainly owing to the problems that had been encountered with the durability of the furnace structure. So, following the example set by Bessemer, in 1864 he opened the Sample Steel Works in Birmingham with an experimental furnace of 1 ton capacity. By the following summer he had succeeded in producing steel from a charge of iron ore mixed with pig iron or scrap metal, the iron ore providing the oxygen required for the refining reactions. A significant improvement in the durability of the furnace lining had been achieved by changing the alignment of the gas and air entry ports to direct the flame away from the roof and downwards onto the bath. A campaign lasting five weeks was reported with the new furnace design, whereas the best that the Martin brothers had achieved was only three or four days. (Almost twenty years elapsed, however, before redesign of the entry ports to introduce the air above the gas port gave better protection to the roof and a marked increase in the interval between the furnace rebuilds).

These achievements still evoked no support from the steelmaking fraternity, so he built a second furnace in which steel was made from a mixture of pig iron, scrap steel and wrought iron rails. Scrap metal could not be incorporated in the charge for the converter, so Siemens was able to claim that he could produce steel in his furnace which was of superior quality and for less cost than could be produced in the Bessemer process. Four companies were persuaded to take up licenses by this claim. Open hearth furnaces were built by Rowan and Company in Glasgow, Barrow Hematite Steel Company, Bolton Steel Company and at Bernard Samuelson's Newport Works in Middlesbrough, but they all experienced major problems, mainly with the durability of the refractory lining, and had ceased to operate by 1870. A fifth license was taken up by the London and North Western Railway Company. Four Siemens furnaces began production of steel for rolling into rails in 1868 at the Crewe railway workshops, using an adaptation of the Siemens-Martin process. This became the first commercially successful open hearth melting shop in Britain.

The Great Western Railway Company placed an order with Siemens in the same year to produce steel rails from scrap wrought iron rails. The ingots were cast at the Sample Steel works, rolled into rails at the Atlas Works of John Brown in Sheffield and installed at Paddington station. When repeat orders were received, Siemens formed a partnership with his brother-in-law, Donald Gordon, and two friends, Lewis L. Dillwyn and Evan Richards. The partners took over a derelict works at Landore by the side of the river Tawe on the outskirts of Swansea, where regenerative furnaces had been in use for some time for the smelting of silver. The Landore Siemens Steel Company was opened in 1868 with eight furnaces of 6 tons capacity and was producing 75 tons of steel per week by mid 1869. The works included also regenerative furnaces for puddling and for reheating the ingots prior to rolling. In the following year, the output had increased to 100 tons per week, but the order book was growing at an even more rapid rate. Land was acquired, therefore, on the opposite side of the river Tawe from the original works. The first British green field
integrated iron and steel works was built on the site with three blast furnaces, sixteen open hearth furnaces of 10 tons capacity, two rail mills, a rod, a bar and a tyre mill. The weekly output of steel had increased to 1000 tons by 1873.

The commercial viability of the open hearth process was assured by this time. It was generally accepted that the quality of the steel produced from the furnaces was superior to Bessemer steel, although Trevor Lodge recounts an unfortunate incident that occurred when a demonstration to illustrate the toughness of the steel was made before a delegation from the Iron and Steel Institute which included Henry Bessemer. When a falling weight of 1 ton impacted on a rail supported at each end the rail fractured instead of bending. A large piece of metal ejected from the fracture narrowly missed Mr Bessemer.57

3.5.2 Open Hearth versus Bessemer Steelmaking
The advantages and disadvantages of the Siemens process, relative to converter practice, were soon recognised. There were two principal disadvantages. The tap-to-tap time for a converter heat was 30–45 minutes, compared with 8–12 hours for the open hearth. The actual heat time for the latter depended on the type of charge and the furnace capacity. Also fuel for heating the charge was only required in a Bessemer melting shop where the metal was not taken directly from the blast furnace. The gas producers had to be fired continuously to heat the Siemens furnaces, although the cheapest grades of coal or coal slack could be used for this purpose provided that the sulphur content was low and the ash did not have too low a fusion temperature.

These detrimental features were heavily outweighed by the advantages of the open hearth. Both processes used a silica hearth and could only handle charges with a low phosphorus content, but the open hearth furnace could process a much wider range of charge materials. Since the heat was supplied externally, a high silica content was not a necessary requirement for the pig iron. In fact, a white pig iron with a low silicon content was an advantage in the charge, for heat was transferred from the flame to the metal via the slag. A thick slag layer acted as a thermal blanket, but the depth of the slag layer decreased as the silicon content of the charge was decreased. As noted above, only very small amounts of scrap metal could be incorporated in the converter charge whereas scrap iron and steel could make up the full charge for an open hearth heat, at much lower cost than for a pig iron charge. Some Bessemer melting shops installed Siemens furnaces to provide a means of remelting the internally circulating scrap metal, including the Bolton Steel and Iron Company (1869) and the Dowlais works (1871).

The metallic yield from a converter heat was usually 85–86% of the charge weight, the loss arising mainly from the elimination of the silicon, carbon and other oxidisable elements from the pig iron and by the formation of a relatively large volume of ferrous silicate slag. In contrast, the yield loss in the open hearth process was only about 2%. Less iron was lost as oxides into the smaller slag volume and the loss from the oxidising reactions was partially compensated by the recovery of iron units released from the iron ore which was charged to supply the oxygen needed for the refining reactions.
The major advantage of the open hearth process was the closer control that could be exercised over the composition and the temperature of the metal at the end of the heat. Iron ore was fed to stimulate the reactions when an unbroken layer of slag had covered the bath and the intensity of the resultant carbon boil was indicative of the state of oxidation in the bath. Turbulence ceased when the free oxygen content was nearly exhausted and the slag layer then acted as a diffusion barrier, retarding the transfer of oxygen from the gas atmosphere to the metal. The rate of the refining reactions could thus be lowered markedly by halting the ore feed and the bath could be held in this state during the time required for the composition of the metal to be assessed from a sample taken from the bath with a long-handled spoon. Refining could be stopped to produce a steel with any required carbon content. Small additions of limestone were often made to displace some iron oxides and to thicken up the slag so that the carbon boil ceased completely at the end of the heat.

While the composition of the metal was being assessed, the temperature of the bath could be adjusted to provide the required degree of superheat by regulation of the damper, in a manner similar to the temperature control in the puddling process. The first hand melter could usually estimate the metal temperature to within ±20°C. If necessary, the boil could be restarted to lower the carbon content further by the addition of more iron oxide. Spiegeleisen, ferro-manganese or ferro-silicon was added as a deoxidant when the required composition had been attained and was given time to react before the metal was tapped into the ladle. If the carbon content of the metal had fallen below the required level it could be adjusted upwards, either by adding preheated pig iron to the bath and allowing time for it to melt and homogenise, or by throwing anthracite coal or charcoal onto the metal steam as it ran into the ladle. Since there was no opportunity for the analysis of a bath sample taken from a converter, a similar close control could not be exercised over the composition of Bessemer steel.

3.5.3 Location and Output

The adoption of open hearth melting was very slow in Britain. By 1873, when the Landore plant was in full production, the output from the process was only 77,500 tons, two thirds of which was produced at the Landore plant. This was insignificant when compared with the output of almost 0.5 million tons from the Bessemer process in that year. At that time few furnaces had an output as high as 50 tons of steel per week. But open hearth production had almost doubled during the next four years and was approaching six times greater by 1883 (Table 7). Some furnaces were then producing up to 150 tons of steel per week. As the list of applications increased for which open hearth steel was preferred to Bessemer steel, many companies now found it advantageous to change their steelmaking practice and, within a decade, acid open hearth steel production exceeded the output from acid-lined converters. Open hearth furnace production showed an increase of 92% during the last decade of the nineteenth century, while Bessemer converter production slowly declined.
Table 7  Open Hearth Steel Production.

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The first companies to take up licenses from Siemens used the process mainly for recycling scrap metal to produce railway rails. Wrought iron rails no longer enjoyed a price advantage over steel by this time and the remaining mills which had been producing iron rails were changing over to rolling steel. But, as with the Bessemer story, the loss of the rail export market to the USA led to a major product diversification.

A flourishing trade in the production of tin plate had been established in Wales. Traditionally, the tin coating was applied to a wrought iron substrate. Attempts to substitute sheet rolled from Bessemer steel ingots ended in failure, for the metal was reported to be 'too springy and inconsistent in quality'. Sheet rolled from ingots of open hearth steel produced at Landore works, however, was found to be satisfactory for plating and there was a rapid growth in this application. Ninety-one Siemens furnaces had been installed in sixteen works by 1878 and 102 furnaces were in use in the following year. Forty-eight of these were located in South Wales and produced almost half of the total output from the acid process in that year. The largest group of furnaces was still located at Landore, but a melting shop containing ten 10 ton furnaces and two 14 ton furnaces had been built over the previous five years at the new Panteg works and six 6-ton furnaces had been installed at the Dowlais works.

After South Wales the second largest concentration of furnaces was in West Scotland. Apart from a small melting shop at the works of Rowan and Company in Glasgow, Bessemer practice had not found favour in Scotland but the open hearth process received a warmer reception. The Hallside works of the Steel Company of Scotland was opened in 1871, initially with the intention of applying a Siemens's rotary direct reduction furnace to the metallisation of the heaps of 'blue billy' iron oxide that had accumulated locally after the production of sulphuric acid from iron.
pyrites. The sponge iron product was then melted in open hearth furnaces. The process proved to be unprofitable, however, and the sponge was replaced by Cumberland hematite pig iron in the furnace charge. The works grew rapidly, with the commissioning of four 6 ton furnaces in 1873 and a further four in 1874. Four 10 ton furnaces were added during the next two years and two 6 ton furnaces were built in 1877 for the production of castings. The output of Siemens steel from the company's works increased from 1200 ingot tons in 1873 to 42,000 tons in 1878. Melting shops, each containing three open hearth furnaces, were also under construction in 1879 for William Beardmore and for Williams and Company at Wishaw. The Mossend Iron Company and David Colville and Sons started ingot production in the following year and additional melting units were installed at the Steel Company of Scotland, giving a total of forty-three open hearth furnaces in Scotland by 1880.

Sheffield, which for most of the nineteenth century had reigned as the largest British steel producer had, by this stage, been pushed into third place following the rapid growth of Siemens steelmaking in Wales and Scotland. The sudden drop in export orders for rails, which had absorbed most of the output in the early years of the Bessemer process, resulted in a temporary check to the growth of the Sheffield works and they were slow to adopt the open hearth process. Eventually William Vickers, Sons and Company installed ten furnaces in the late 1870s at the River Don works, followed by the construction of six furnaces at the Grimesthorpe, Sheffield works of Charles Cammell and Company. John Brown built one furnace at the Atlas works in 1879, but the total production of open hearth steel from the Sheffield district was only 21,000 tons in that year, which was a little under one eighth of the total British output.

A total of thirteen open hearth furnaces were in use at the end of the 1870s by the Bolton Iron and Steel Company and by the railway workshops in Lancashire, giving an annual output of 15,000 tons, but the converter process remained supreme at the North West Coast works. Similarly, the Siemens process had barely gained a foothold in the North East Coast region, where only five furnaces had been built by 1879, although the Consett Iron Company was starting to build a Siemens melting shop.

A major development in the use of steel followed the decision by Lloyds Register in 1877 that open hearth steel was suitable for use in ship building. Some plates rolled from steel made in a converter had been used for ship construction in the 1860s, but Bessemer steel was not generally considered to be suitable for the purpose. The trade grew rapidly after the Lloyds agreement. A small naval vessel built from steel supplied by the Landore works was launched in 1877 and a second vessel was launched in the following year. By 1880 a total of 114,000 tons of steel shipping was under construction. Many works in South Wales and in Sheffield installed plate mills to supply the trade, but the major growth in this market occurred in Scotland. New works were built there to meet the demand and, by 1885, seventy-three acid lined open hearth furnaces were in use in Scotland compared to a total of 152 furnaces in England and Wales. The growth in the trade was
accompanied by a fall in the price of ship plate to about £11.00 per ton in 1880 and to £6.75 per ton in 1885.\(^6\)

In addition to the production of ship plate, the Sheffield firms of Brown, Cammell and Vickers began to supply armour plate made from steel. Charles Cammell and Company patented a process for making compound armour plate in 1876, in which a layer of eutectoid steel was cast onto a wrought iron plate. John Brown and Company patented a similar process in the following year. But all-steel armour had replaced the compound plate by 1888, by which time a strong export trade for armour had been developed.

The successful adoption of open hearth steel for the production of tin plate encouraged seven of the South Wales tin plate manufacturers to install open hearth furnaces during the 1880s. These were relatively small melting shops, which proved uneconomical to operate, and only the South Wales Iron and Tinplate, Melyn, Cwmfelin and Upper Forest tin plate works survived beyond the end of the century. This did not deter further development, however, and the Dyffryn, Pontardawe, Polymister and Grovesend tin plate companies installed open hearth furnaces in the 1890s. Two new works were opened at Briton Ferry, near Swansea, primarily to supply tin plate to the plating works.\(^6\)

Apart from tin plate production, the bulk steel industry that had been established at the Heads of the Valleys in South Wales was becoming uneconomic, for the local iron ore deposits were nearing exhaustion. Ore imported from Spain via the Cardiff docks required transportation by rail or canal to the works. The Dowlais company at Merthyr Tydfil began the construction of a new works at East Moors Cardiff, to reduce the transport costs. A melting shop containing six 30 ton furnaces was opened at the new works in 1895 and this marked the beginning of the ultimate demise of the Merthyr iron and steel works.

Two 25 ton and three 40 ton open hearth furnaces were added to the melting capacity at the Colvilles works in Scotland in the mid 1890s and by the end of the century the company was operating twenty furnaces. A grand total of 116 furnaces were in use in Scotland by 1897. The North East Coast region was slow to adopt the Siemens process and the Consett works remained as the major operator, with twenty furnaces in operation in 1882 and twenty-nine in use by 1893. Thomas Firth and Company began open hearth steel production in Sheffield in 1884 with one 10 ton and two 25 ton furnaces. Brown Bayley, Hadfield and Samuel Fox all built Siemens furnaces during the 1890s, but only eleven works in Sheffield were making open hearth steel, using thirty-six furnaces, by the end of the century.

The maximum capacity of a furnace increased steadily from the six tons size of the original installations at Landore to about 50 tons by the 1890s. The average size was then 30 to 40 tons. Following its invention in America, the first Wellman mechanical charging machine in Britain was installed in 1898 at the Llanelli works\(^6\) and the second one was installed by Vickers, Son and Maxim in the following year. All the other furnaces were charged by hand and this constrained the growth in the furnace capacity. It was also claimed at the time that combustion was less efficient in the larger furnaces, resulting in an output of four charges per
day from furnaces of 20–25 tons capacity but only two charges per day from 50 ton furnaces.\textsuperscript{66}

Sir William Siemens died on the 9 November 1883, aged 60. The regenerative furnace and steelmaking process bearing his name, which continued in production in various parts of the world for 100 years after his death, perpetuate his memory. He is rarely remembered for his efforts to establish a direct reduction process for the treatment of iron ores, but he provided the basis from which the modern direct reduction processes have been developed. Credit is also rarely given to him for the invention of the electric arc furnace. He patented designs for both direct and indirect arcs in 1879. A demonstration furnace was erected in 1881 at the Siemens brothers' Charlton Works,\textsuperscript{12} but the high cost of electricity at that time made the project non-viable. The first commercial electric arc furnace in Britain was not commissioned until 1910 at the works of Edgar Allen and Company Ltd.

\section*{3.6 Basic Steelmaking}

\subsection*{3.6.1 The Basic Bessemer or Thomas Process}

The pig iron, which was smelted from the majority of iron ore deposits found in Britain, was not suitable for refining by Bessemer's original process because the phosphorus content was too high. This was particularly frustrating for the iron industry that began to develop in Eastern England, initially with the working of the Cleveland ore deposits and extending subsequently to the Lincolnshire and the Northamptonshire ore fields. Supplies of indigenous hematite ore were not adequate to satisfy the growing demand from the steelmakers and freight costs of £0.75 to £1.00 per ton for imported Spanish hematite ore added significantly to the costs of production.

The extensive removal of phosphorus from pig iron during puddling was attributed in the early 1860s to the liquation of iron phosphide from the metal at the relatively low temperatures to which the metal was exposed in the process.\textsuperscript{16} It was soon recognised, however, that a basic or lime rich slag was necessary in order to remove phosphorus from the charge at the higher temperature that prevailed in the new steelmaking processes. This type of slag could not be contained in furnaces lined with the traditional acidic refractory materials and a new type of lining was required. Attempts were made in Germany in the late 1860s to develop bauxite and magnesia as lining materials, but the work came to a halt in 1870, at the outbreak of the Franco-Prussian war.

The Dowlais works in Merthyr Tydfil acquired a high reputation during the nineteenth century for the many entrepreneurial investigations that were carried out on the premises. Several people started their career with the company and then moved on to senior management posts elsewhere in Britain. One of these people was George Snelus,\textsuperscript{67} who was employed initially as a chemist at the works. In this capacity, he began experiments to develop a basic lining for the Bessemer converter. He found that it was 'possible to make bricks out of lime or (magnesian) limestone, provided that the lime when used was crushed quickly, compressed and
fired before it had time to absorb moisture'. The lining was described in British Patent 908, issued in 1872.

He refined a charge of 100 kg of Cleveland iron ore containing 1.5% phosphorus in a small converter lined with bricks made from lime and produced a steel containing only 0.018% phosphorus. Difficulties were encountered, however, when attempts were made to use the lime bricks to form a lining in larger converters. The experiments were halted when Snelus was appointed works manager and subsequently general manager of the West Cumberland Iron and Steel Company, which was one of the major producers of hematite pig iron. After a few years in this post he was able to resume the experiments with the use of a basic slag and reported a successful series of results when Sidney Gilchrist Thomas presented his seminal paper on basic steelmaking in 1879.

There is no indication whether or not Thomas, a clerk at the Thames Police Court who had studied chemistry at evening classes, was aware of the Snelus patent when he began experiments on dephosphorisation. He worked with his cousin, Percy Carlisle Gilchrist, who was a chemist at the Blaenavon works in South Wales. They had some success in lining a small vessel which accommodated a 3.5 kg charge with bricks made from hard burned lime and bonded with water glass (sodium silicate). The manager of the Blaenavon works then provided facilities for larger scale trials, using a cupola into which tuyeres were inserted from the sides to serve as a fixed converter. Thomas subsequently obtained patents for lime-based (British Patent 289, 1878) and dolomite-based (British Patent 908, 1878) converter linings using hard-fired pre-shrunk refractory materials.

A paper describing the results obtained by Thomas and Gilchrist was tabled but not presented at the autumn meeting of the Iron and Steel Institute in 1878. The paper was noticed subsequently by E. Windsor Richards, another ex-Dowlais man who was now the manager of the Eston works of Bolckow Vaughan and Company at Middlesbrough. He contacted the authors and arranged for trial melts using Cleveland pig iron. After three charges had been melted successfully in the presence of Richards and his works chemist, J. E. Stead, he persuaded the cousins to transfer their development work to the Bessemer melting shop that had been opened in the previous year at the Eston works. Two 1.5 ton capacity converters were made available for their use but the early experiments proved to be frustrating, for only a few heats could be processed before the linings made with lime or dolomite bricks had to be replaced. Dolomite powder mixed with water glass and rammed into position burst the shell of the converter as a result of the rehydration of the lining.

Bonding with lime gave a better performance. Dolomite mixed with cold tar proved to be too stiff to ram into position, but a durable lining was obtained when the dolomite was mixed with hot tar and rammed to form a lining in the converter while the tar was still hot (British Patent 1313, 1879). The shape of the converter reverted to the earlier form with a concentric nose, because this facilitated the lining operation. A firebrick lining in the nose, together with the change of shape, helped to reduce the rate of build up of accretions and simplified their removal.
Although the problem of lining the converter to contain a basic slag had now been solved, the steelmaking results were disappointing, for the transfer of phosphorus from the metal to the slag was very erratic. Various modifications to the refining practice were tried. Pre-empting developments which only achieved commercial significance in mid twentieth century, J. E. Stead described attempts which were made to improve phosphorus removal by blowing powdered lime into the converter. It was thought that the lime powder would combine with the silica as it was formed by oxidation from the iron and carry it into the slag, leaving the iron oxides produced within the bath to combine with the phosphorus. Only about half of the phosphorus was removed from the metal with this approach, however, and the trials were eventually discontinued because of problems encountered with the lime-blowing equipment.

Whilst he was observing the trial heats that were made for Windsor Richards with the basic lined cupola at the Blaenavon works, Stead had noted that in one experiment the blow had been continued for a short time after the carbon flame had dropped. The steel made in that heat contained only 0.11% phosphorus, whereas the other two heats in which the blow had been halted with 0.3–0.4% carbon remaining in the metal still contained respectively 0.41 and 0.88% phosphorus. On the basis of this observation, he reasoned that both basic and strongly oxidising conditions were required to achieve effective dephosphorisation at steelmaking temperatures, so the element would not start to be transferred extensively into the slag until carbon had been almost eliminated from the melt. Based on this reasoning he proposed that the blow should be continued after the flame had dropped. An after-blow of about 3 minutes was found to result in almost complete removal of the phosphorus from the metal. A description of the modified practice to include an after-blow was written up as an appendix to the paper that Thomas had first submitted in 1878 when it was eventually read at the 1879 Spring Meeting of the Iron and Steel Institute.

Larger quantities of spiegeleisen than were normally required with the acid converter practice were needed to deoxidise the bath following the after-blow. Some reversion of phosphorus from slag to metal occurred if a violent turbulence was caused by this addition, but the extent of the reversion was found to be small when the deoxidant was added slowly. Eventually the practice was developed of decanting most of the slag at the end of the after-blow and adding a small amount of lime to thicken up the remainder of the slag before the metal was deoxidised.

The oxidation of silicon had provided almost all the thermal energy required for the acid Bessemer process. But this element was not wanted in the basic converter charge, for each mole of silica formed by oxidation from the pig iron required the addition of more than two moles of lime to neutralise it and form a basic slag. The oxidation of phosphorus during the after-blow was found to be exothermic, but one gram of phosphorus provided only about 75% of the amount of heat that was released by the oxidation of 1 g of silicon. Compared with the acid practice, therefore, additional heat was needed to melt the lime and form the slag in the basic practice. It was found that about 2.5–3.0% of phosphorus was required in the
charge if a white pig iron containing about 0.5% silicon was refined in a vessel with a basic lining.

The highest phosphorus contents normally found in pig iron produced from British ores did not reach this level, but a temporary solution was found. Vast heaps of puddling cinder rich in phosphorus had accumulated in the vicinity of the malleable iron works and this cinder was added to the blast furnace charge to raise the phosphorus content of the pig iron. The cinder stocks were soon depleted, however, and in view of this, it is perhaps not surprising to find that British companies were slow to adopt the Thomas process. In marked contrast, there were abundant supplies of phosphoric iron ores available on the continent, which produced pig irons well suited to refining in the Thomas process. The take up of licenses was rapid in Germany, where the first basic heats were blown in 1879 and shortly thereafter in Austria. Belgium and France also soon adopted the practice.

The first melting shop in Britain to operate the Thomas process was located at the Eston works of Bolckow Vaughan. The original 1.5 ton vessels that had been used for the development of the basic lining were supplemented by the addition of two 15 ton vessels in 1879, two more in 1881 and a third pair in the following year to give a total steelmaking capacity of 225,000 tons. The second melting shop to be built, containing two 8 ton converters, was also opened in 1879 at the Sheffield works of Brown, Bayley and Dixon. The managers of this works made the original proposal to use an oil-bonded lining and developed the practice of decanting the slag before the deoxidisers were added. The Lilleshall Company in Shropshire opened a melting shop containing three 7 ton converters in 1882 and the North Eastern Steel Company, Middlesbrough, commissioned four 10 ton vessels in the following year. Most of the output from these works was rolled into rails.

Several basic converters were commissioned in 1884, including three 10 ton units at the Staffordshire Steel and Iron Company, one 4 ton vessel at Sellerhall, Middlesbrough, four of 10 ton capacity at the Glengarnock works and three to hold 7 tons at the Wishaw works in Glasgow. The use of the basic converters at Brown, Bayley and Dixon had ceased by that date, following the departure of the melting shop manager to become manager of the North Eastern Steelworks, leaving a total of twenty-four converters operating the Thomas process in seven works. Two 7 ton vessels were built in 1890 at the Leeds Steel works, but the total output of Thomas steel had by now started to decline. There was a recovery to reach a new peak output in the last year of the century (Table 6) but only four melting shops in Britain were then operating the Thomas process. The proportion of Bessemer steel made in converters with a basic lining had increased, however, from 11.5% of the total output in 1884 to 13.9% in 1899.

3.6.2 The Basic Open Hearth Process

The adoption of a basic lining for the Siemens furnace was a natural progression from the successful evolution of the basic converter, but it was a slow development. Following earlier trials on the continent, the first open hearth furnace in Britain with a basic lining was built in 1884 at the Brymbo Steel Company under the direc-
tion of John Henry Darby, a direct descendant of the Darby family of Coalbrookdale. The furnace had a rammed hearth of dolomite, which was isolated from the silica walls and roof by a layer of chrome ore. Chromium oxide was classed by then as a neutral material. Five years later the Bell Brothers of Middlesbrough attempted to use chrome ore to form the hearth instead of dolomite, but it did not prove to be sufficiently durable.

The initial trials at Brymbo were made with a furnace of 5 tons capacity. When success was achieved, the melting shop gradually expanded to accommodate four 12 ton and two 20 ton basic furnaces. For several years this remained the largest basic open hearth plant in Britain. The Patent Shaft and Axletree Company at Wednesbury was the second works to use the process, starting production in 1885. Almost half of the total number of basic Siemens furnaces in use in Britain in the closing decades of the nineteenth century were operating in Staffordshire. The second largest grouping was located in South Wales. But a new steelmaking region, which was to become a major centre in the next century, had already begun to emerge on the Lincolnshire ore fields when two 15 ton furnaces were installed in 1888 at the Frodingham Iron Company. Two 20 ton furnaces were added in 1895 and a 30 ton furnace was built in 1898.

The basic open hearth process was adopted when steelmaking began in Lincolnshire because the local iron ores contained on average less than 1.0% phosphorus. This concentration was too high for processing of the pig iron produced from the ore in the acid processes, but much too low for refining in the basic-lined converter. The puddling process had not been applied in the locality, so the blast furnace charge could not readily be enriched in phosphorus by adding tap cinder. The thermal requirements of the open hearth furnace were supplied by the combustion flame, however, and phosphorus was not required in the process as a source of heat. With a typical charge at that time comprising 60–70% of pig iron and the remainder of scrap metal, the phosphorus introduced by the pig iron was diluted by the scrap and the bath rarely contained more than 1.5% phosphorus at the start of refining. About 40% of this was found to have transferred to the slag by the stage where most of the silicon and manganese had been oxidised from the metal and 95–98% could be removed into the slag by the end of refining. As a result of the lower phosphorus content in the charge, the amount of lime required per ton of metal for the formation of the slag was only about half of the quantity required in the basic Bessemer process. The difference between the metallic yields from the two processes was even more marked, because of the lower metalloid content of the pig iron used in the basic open hearth process and the recovery of iron units from the iron ore added as an oxidant.

Twenty-seven Siemens furnaces with basic linings were in use in Britain in 1890, compared to 302 furnaces with acid linings. The balance had moved only slightly towards the basic process by the end of the century. The distribution of the furnaces around the steelmaking regions was then as shown in Table 8. Eight companies were listed as operators of the basic open hearth process in 1898, namely the Brymbo, Frodingham, Glengarnock, Park Gate, Round Oak, Skelton, South
Table 8 Distribution of furnaces around steelmaking regions.

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<tr>
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Staffordshire and Wigan companies. Just over six% of the open hearth steel made in Britain was then produced by the basic processes (Table 7).

3.6.3 Sulphur Removal
Steel produced by the basic processes soon gained acceptability for use in many of the applications that had been developed for the acid steels. Basic open hearth steel received an additional boost in 1890 when both Lloyds Register of Shipping and the British Admiralty passed it as suitable for use in the construction of ships. Following the solution of the phosphorus problem, attention switched to the control of the sulphur content, which had become recognised as the cause of hot shortness and poor ductility in some steels. By the 1870s it was known that the operation of a blast furnace with a high hearth temperature to produce a pig iron with a high silicon content usually resulted in a low sulphur content in the iron, and vice versa. About 55 per cent of the sulphur could be removed from the pig iron during wet puddling, but the concentration actually increased slightly during acid steelmaking, owing to the oxidation of the silicon and carbon from the iron with no compensating loss of sulphur. The sulphur content of the charge for an acid Bessemer converter could be lowered by the use of a pig iron with a high silicon content, but this practice was not feasible with the Thomas process. It was then found that up to half of the sulphur could be transferred from the metal into a lime-saturated slag. The proportion removed from the metal increased with increase in the volume of the saturated slag, but the thermal load also increased, placing a limit on this means of control.

A variety of techniques were devised in an attempt to produce steel with a low sulphur content. Some were intended to limit the amount of sulphur in the pig iron by operating the blast furnace with a slag as close as possible to lime saturation, or by incorporating several per cent of manganese ore in the blast furnace charge to fix the sulphur as MnS. Lowthian Bell aimed to remove most of the silicon and some of the sulphur and phosphorus from a high silicon pig iron by pouring the metal through a synthetic slag as it was tapped from the furnace. The practice was not found to be commercially viable at the time, but a variant on this approach was exploited later in France as the Perrin process.
A very different approach was adopted by E. H. Saniter\textsuperscript{75, 76} in an experimental programme that was started in 1890 at the Wigan Coal and Iron Company. The lime content of a basic open hearth slag was usually limited to a maximum of 55% to ensure sufficient fluidity. Using anhydrous calcium chloride as a flux, Saniter was able to increase the lime content to about 60% and found that between 80 and 90% of the sulphur could then be transferred into this more basic slag. The operating procedures and performance were detailed in three patents (British Patents 8612, 17692 and 23534) issued in 1892. In a modification of the process first described by Bell, one of the patents described placing molten lime and calcium chloride in a ladle to treat the metal as it was tapped from the blast furnace. Alternatively, 18 kg of calcium chloride per ton of metal could be added to the molten charge in a basic Bessemer converter or a basic open hearth furnace. Fluorspar could be substituted as a flux for part of the calcium chloride. These techniques were soon widely applied. By the closing years of the century, however, most large melting shops contained at least one hot metal mixer. It was then claimed that the cheapest way to lower the sulphur content to an acceptable level in the steel was to add about 1.5% of manganese, in the form of spiegeleisen or ferro-manganese, to the metal in the mixer.\textsuperscript{26} This became the normal procedure for the production of steels for the less demanding applications.

3.7 Molten Metal Postscript

The increases in the scale of production of iron and steel that were achieved in Britain during the nineteenth century are unlikely ever to be repeated. Vast improvements were effected in the thermal efficiency of the operations. Almost all the wrought iron and steel produced was made from virgin materials in 1800, but a century later a significant portion was melted from recirculated scrap metal, reducing markedly the fuel requirements. Coal consumption per ton of metal produced in the blast furnace had decreased by about 75%. In 1800, about 7 tons of coal were consumed for each ton of steel produced by the crucible process, but the energy requirements fell dramatically with the introduction of the bulk steelmaking processes. The average coal consumption per ton of metal made in an open hearth furnace varied from about 0.5 tons with a hot metal charge to 1.0 tons for a cold charge of pig iron and scrap metal. Even greater savings were made with a Bessemer converter when it was fed with molten metal from a hot metal mixer, for fuel was then required only for the blowing engines, for preheating the deoxidiser and for maintaining the temperature in the hot metal mixer.

The manpower requirements per ton of metal had also fallen as the capacity of the individual production units had increased and as the labour-intensive puddling operation had largely been phased out. Over a twenty year period, up to 1899, the average annual output from a Bessemer converter had risen from 9900 tons to a little over 29,000 tons, while the output from an open hearth furnace had increased from 1715 tons to 6871 tons.

By modern standards the control of the processes was still very primitive at the
end of the nineteenth century, but major advances had been achieved. Significant progress began to be made only after reliable procedures had been developed for the chemical analysis of metal and slag samples. Methods for the analytical determination of some elements in iron and steel were published during the first half of the century but, even in the late 1860s, a complete analysis of a sample of plain carbon steel would normally take seven or more days to complete. Very few works employed chemists. G. Snelus and C. Parry in South Wales and J. E. Stead in the North East Coast region had established reputations as works chemists by 1880 and four of the larger Sheffield works were each employing an analyst by that time, but these were the exceptions to the general situation. Progress accelerated during the last two decades of the century and the Journal of the Iron and Steel Institute began to include a section giving brief accounts of new methods of chemical analysis as they were devised. Although the analysed concentrations were usually given to three decimal places, the poor reproducibility between analysts was widely recognised. In an effort to improve the accuracy, the first series of standard steels for analytical calibration was issued in 1889 by the British Association.

As more use was made of chemical analysis, the relationships between the composition of the metal and other characteristics such as the appearance of fracture surfaces slowly began to be recognised. The selection of the materials to make up a charge and the additions or adjustments made during the course of refining then began to be based on reasoned arguments instead of the traditional trial and error approach. But a minority of iron and steel works contained a chemical laboratory at the end of the century and a significant proportion of casts still failed to meet the targeted specification, despite the relatively generous tolerance limits that were usually imposed.

4. FABRICATION

4.1 Ingots and castings

Before the opening of Bessemer’s works in Sheffield, there had been relatively little change in the procedures that were used to produce steel ingots since the introduction of split cast iron moulds in the late eighteenth century. The most significant change was a gradual increase in the size of the ingots from about 9 kg in 1800 to 30 kg by midcentury. The moulds continued to have a square cross-section, but the internal width had increased to about 90 mm. The increase in the size of the ingots correlated with the corresponding increase in the capacity of the crucibles, for the entire contents of one crucible were normally teemed into one mould. Larger ingots, up to about 100 kg in weight, were occasionally produced by teeming two or more crucibles into one mould in a process which became known as doubling-up.

The larger quantities of metal produced from one heat in a Bessemer converter required a radically different approach to ingot production and Henry Bessemer was largely responsible for the initial developments. Lip-pouring ladles were in
regular use in foundries and were adopted to carry the metal from the cupola to the converter. But they were not suitable for pouring the metal into the narrow mouth of a mould, so Bessemer designed a bottom-teeming ladle with a stopper rod to regulate the metal flow. He also introduced the use of larger unsplit, parallel sided, cast iron moulds with a hydraulic ram in the base to eject the solidified ingot.

For many years the lack of soundness in the ingots was a major cause of concern. Before the introduction of deoxidant additions in crucible steelmaking, it was normal practice to superheat the metal and to then retain it in the furnace for at least 1 hour to allow time for any residual oxygen to react with the carbon in the iron. The crucible was then removed from the melting hole, transported to the teeming station and the metal was poured immediately into the mould. Since the crucible was both hot and heavy the teeming was usually done as quickly as possible, allowing little time for the superheat to dissipate. The subsequent contraction as the metal cooled and solidified caused the formation of a large shrinkage cavity or pipe. It was normal practice to cut off for scrap all that portion of the ingot containing the pipe, resulting in a severely reduced yield of saleable metal from the heat. A major improvement was introduced in 1861 by Robert Forrester Mushet (British Patent 1310, 1861) who halted the teeming temporarily when the crucible was almost empty while a clay pipe or ‘dozzle’, preheated to a bright red heat, was inserted into the top of the mould to reduce the cross-section. This delayed the solidification of the residual metal, decreased markedly the depth of the pipe and increased the yield of usable material.

The dozzle could only be used with ingots of fairly small cross-section. It could not be produced in sizes large enough for use with the bigger ingot moulds when they were first introduced for casting Bessemer steel. The mould size tended to increase to maintain relationship with the number and with the capacity of the converters in use in a melting shop. Tapered moulds were soon introduced. Initially they were mounted big end down in the casting pit to facilitate stripping from the ingot when the metal had solidified. This practice continued until it was realised that a secondary pipe, which formed in the lower section of the ingot, could be avoided if the moulds were used with the widest cross-section at the top. The refractory-lined feeder head for use on the large moulds was not introduced until the closing years of the century.

Many ingots were rejected because of the appearance of a ‘honeycomb structure’ caused by the evolution of gas during solidification. It was eventually recognised that there was an inverse relationship between the volume of the pipe and the volume of the porosity and that the amount of gas released on solidification tended to increase at very low carbon contents in the steel. There was no agreement, however, concerning the gaseous species that was responsible for the formation of the blowholes and no consideration seems to have been given to controlling the volume of the blowholes to balance the solidification shrinkage. Rimming steel practice was not introduced during the nineteenth century. The main effort was directed towards preventing the gas release. The superheating and holding practice used by the crucible steelmakers was not effective when applied to the lower
carbon steels made in the Siemens furnaces. It could not be applied with the con-
verter process because of the loss of heat from the melt which would occur in the
absence of any oxidising reactions.

The porosity was diminished but not entirely eliminated when spiegeleisen was
added to the melt as a deoxidant. This alloy usually contained 10–15% Mn and
about 5% C, so a sufficient quantity could be added to kill the melt when medium
or high carbon steels were being produced, but the amount that could be added
was severely limited when low carbon steels were being made in the open hearth
furnace or in the converter. Ferro-manganese containing up to 80% Mn, was first
produced in 1875. It was soon substituted for spiegel as a deoxidant and the Ebbw
Vale and John Brown works each designated one blast furnace for the production
of the alloy.

The formation of blowholes created serious problems when high integrity cast-
ingings such as gun barrels, were being produced. In a patent issued in 1856, Bessemer
proposed the prevention of porosity formation by the application of pressure to the
solidifying casting. The mould and the ladle were mounted inside a cast iron vessel,
which was made airtight and then pressurised after the mould had been filled. The
technique was not exploited until, in 1865 and under license from Bessemer, Joseph
Whitworth started to produce gun barrel castings through the application of a
pressure of up to 1.4 kN m⁻², to a chamber containing the mould box immediately
after the mould had been filled. Three years later, R. Gordon proposed the casting
of ingots under vacuum, but this was not feasible on a commercial scale for there
was no simple means then available for the attainment of the low pressure
required. Techniques of this type were not generally pursued, however, after T.
Nordenfelt claimed (British Patent 8269, 1885) that blowhole formation could be
eliminated by the addition to the melt of a small amount of aluminium. Indicative
of the level of scientific understanding at that time was a paper that ascribed the
beneficial effect of the addition of 0.5–1.0% aluminium to the sudden lowering of
the melting point of the steel by 100–270°C. This proposed mechanism was thought
to be worthy of detailed coverage in a Presidential Address to the Iron and Steel
Institute.

Evidence was first presented in 1881 of carbon, silicon and sulphur segregation
into 'those portions of the ingot which remained fluid the longest, leaving iron and
manganese in excess in the portions from which they have liquated'. Although
the problem was recognised, no practical steps appear to have been taken to mini-
mise segregation in the moulds. From 1888, some attempts were made to produce
sound and homogeneous components by centrifugal casting, but this technique
also made little progress before the end of the century.

The production of artefacts in cast iron was a well-established trade by the start
of the nineteenth century, with an annual output of about 20,000 tons of castings.
Production increased rapidly over the next few decades, stimulated initially by the
demand arising during the Napoleonic wars, but in response also to the require-
ment for beams and columns for the erection of the new factories and workshops.
Castings were needed for construction of the stationary engines which were rap-
idly supplanting the water wheel to provide motive power. The foundry proprietors vied with each other to produce both functional and ornate products, reaching an artistic peak in the late Victorian era. Examples of the fluted columns with decorated bosses produced during that period can still be seen at the Kew Bridge Engine Trust in London, the Papplewick Pumping Station in Nottingham and other industrial museums. The growth of the foundry industry was accelerated also by orders for wheels, tyres, axles and other components for the construction of railway engines, wagons and carriages as ‘railway mania’ took hold of the British public. By this time, the use of a finer and more refractory facing sand in the moulds gave improved surface finishes on unmachined castings.

Apart from a few small artifacts that were cast in crucible steel, up to the late 1850s all ferrous castings were made in cast iron. The skills of the founder in blending a variety of pig irons for the cupola charge to meet the strength, malleability, wear resistance and other requirements in the castings had increased significantly by this time. Only a small percentage of castings were rejected because they did not meet the specification, but control by ‘rule of thumb’ remained the norm throughout the nineteenth century.

Engineering developments led to a demand by midcentury for stronger and tougher components with thinner wall thickness to lower the weight. Following the pioneering work in the production of large castings from crucible steel in 1855 by J. Meyer at the Bochum Verein works in Germany, William Vickers began the production of steel castings in 1856 at the Naylor Vickers works in Sheffield. An issue of *The Engineer*, dated 29 January 1858, contains an eyewitness account of the teeming in 8 minutes of ninety-two crucibles into a mould to produce a steel casting weighing 1100 kg. A bell weighing 2650 kg was cast from the contents of 105 crucibles in 1860 at the Millsands works. Six years later a shaft for a ship’s engine was forged from a 25 ton ingot that had been teemed from 576 crucibles and in 1874 Thomas Firth and Company made a 20 ton ingot from 628 crucibles for forging into a gun barrel. Multiple teeming operations had to be carried out with a military style precision. The crucibles were lifted from the melting holes and carried in procession to arrive at the teeming station at intervals that ensured an unbroken stream of metal entered the mould, yet avoiding a delay whilst waiting to empty the crucible which could result in a loss of fluidity in the metal.

The multiple teeming practice survived for only a relatively short time span. Within twenty years from the first application in Britain, it had been superseded by castings made from bulk melts produced in the open hearth furnace or in the side blown converter. The steel foundry trade developed rapidly in the Sheffield area and when R. A. Hadfield transferred his foundry from the original Newhall Road site to the East Hecla works in 1894, the new plant was described as the largest foundry in the world for the production of steel castings.

4.1.1 Continuous Casting
The continuous casting of steel is usually regarded as a twentieth century development, but the pioneering work was undertaken by Henry Bessemer. He had
obtained patents in 1846 for the continuous casting of thin sheets of tin and lead and also for the production of glass plate. Ten years later, he obtained a further patent, which described the pouring of molten steel into a narrow gap between two water-cooled rolls, which rotated slowly on horizontal axes. The emerging metal strip was fed on a curved track between guide rolls and cut-off shears, similar to the arrangement described in his earlier patents for casting the non-ferrous metals.

Bessemer conducted his experiments in secrecy in the evenings after his employees had left. He melted the steel in a furnace, which was used during the daytime for producing copper alloys for the manufacture of the 'gold' powder and paint, at his factory built in the garden of his Baxter House residence. The crucibles were then carried some distance to the casting machine. Problems with the operation, such as loss of heat during transfer of the metal to the casting machine, adhesion of the metal to the rolls giving a poor surface quality and difficulties in preventing the metal from escaping from the ends of the rolls, proved insuperable. The experiments were eventually abandoned, but a small sample of the strip steel which he produced, less than 2 mm thick, is preserved at the offices of the Institute of Materials. In 1891, seven years before his death, Bessemer wrote up a description for the construction and operation of thin strip casters (Fig. 9). The designs included a perforated tundish to distribute the molten metal uniformly across the length of the rolls and the use of flanges to prevent the escape of metal from the ends of the rolls. Five years earlier he had written that

Possibly some day or other a tin plate manufacturer may be found to have sufficient courage to try and produce by this means endless sheets of thin plate iron as our paper makers have, in their trade, long since learned to do with perfect success.

Fig. 9 Bessemer thin strip continuous casting machine (J. Iron Steel Inst, 1891 (2), Plate IV).
Another century was to pass before the production of thin steel strip became a commercial reality.

4.2 Mechanical Working

4.2.1 Rolling and Forging

The four rolling mills, designed and built by Henry Cort between 1782 and 1790, for the production of wrought iron bar had achieved a high reputation by the dawn of the nineteenth century. The largest of these mills, at the Cyfarthfa works in Merthyr Tydfil, was producing 60–70 tons of bar iron per week in 1803. Many other works erected rolling mills of this type when Cort’s patent lapsed in 1800. The rolls were usually driven directly from a water wheel, which restricted the speed of rotation and only limited deformation could be achieved before the stock had to be returned to a furnace for reheating. This in turn limited the minimum cross-section that could be produced at a reasonable cost. The steam engine replaced the water wheel, more rapidly for driving rolling mills than for many other purposes, when it was realised that higher rolling speeds could be attained by this means, with a consequent increase in the amount of deformation that could be achieved before the metal had to be reheated.

The original rolling mills were all of the two-high, non-reversing design. When the metal had emerged from an active rolling pass the end of the stock had to be lifted manually from the run-out table and returned over the top roll prior to the next pass, so the metal was undergoing deformation for less than half the time that elapsed between successive reheating. A marked improvement was achieved and smaller cross-sections could be produced following the introduction of the three-high mill, allowing deformation of the stock to occur as it passed through the rolls in both forward and backward directions. A three-high mill was in use before 1815 at the Bilston works in Staffordshire, but several decades elapsed before they were in general use. Difficulty was frequently experienced in designing the shape of the rolling passes to avoid the production of slightly distorted shapes or the presence of fins on the finished product. A procedure that had been advocated by Fleur in France was adopted in the 1820s in which the penultimate pass produced an oval or a diamond shape when rolling respectively round or square products and with no reduction in the cross-sectional area in the final pass.

Pack rolling mills for hot rolling thin iron sheets for use in the tin plating trade had been established during the eighteenth century. The number of mills used for this purpose increased rapidly as the demand grew and a flourishing export market for tin plate was developed in the first half of the nineteenth century. South Wales and Monmouthshire monopolised the trade, although there were a few short-lived ventures elsewhere. The first attempts to apply cold rolling for the production of the tin plate sheets were made in about 1820. The practice developed slowly, but by 1854 Samuel Fox and Company at Stocksbridge near Sheffield, had installed cold rolling mills to produce strip for the manufacture of pen nibs, clock springs and measuring tapes. Hot rolling con-
tinued, however, as the principle means of thin strip production to the end of the century.

Following Birkinshaw's invention of the rail mill in 1820, several works in South Wales installed rail mills. The rails for the Liverpool-Manchester railway were rolled at the Pennydarren works in 1830 and the Dowlais works soon acquired an international reputation for the quality of its wrought iron rails. The Welsh manufacturers dominated the trade for almost fifty years, until wrought iron was progressively replaced by Bessemer steel rails. When the machining of profile roll passes for rolling rails had been mastered, it was a relatively simple development to progress to the production of rolled structural beams and girders. By 1859 a Goat mill at the Dowlais works was rolling 'H' section joists, 450 mm deep, in 15 m lengths. A different product was developed in the Midlands where, in 1844, John Spencer of West Bromwich patented a hot and cold rolling process for the production of corrugated iron sheets. In 1800, the balls of malleable iron were still being taken from the puddling furnace to a water-powered helve hammer where most of the slag was expelled as the mass was forged into a shape that was suitable for rolling. Some works replaced the helve hammer with a crocodile squeezer, but otherwise there was little change in practice before James Nasmyth designed the steam hammer in 1839. Less massive foundations were needed for the double action steam hammer, which was introduced a few years later, and they were soon widely adopted. The production of forged components now began to increase steadily and in 1852 the Sheffield firm of Thomas Firth and Sons introduced the practice of forging gun barrels. The greater deformation force which could be exerted by a steam hammer allowed larger masses of metal to be deformed and simplified the welding together of two or more blocks of wrought iron. This in turn made possible the manufacture of longer rails and joists, such as those produced on the Dowlais Goat mill. Prior to this development, the few plate mills in operation could produce boilerplates of only relatively small area.

The problem of manipulating the metal stock between the rolling passes and between rolling stands increased when several blocks of iron were consolidated to form a larger mass and was further exacerbated when larger ingots were produced from Bessemer converter steel. An improvement was obtained with the introduction by J. G. N. Alleyne of idler rolls and mechanical traversers (British Patent 825, 1861), which were mounted before and behind the rolling stands to move the stock. It was soon recognised, however, that a more rapid rate of deformation could be achieved with less manual effort if a number of rolling stands were arranged in a line.

A design for a continuous rolling mill was patented in 1861 by Charles White at the Taff Valley works at Pontypridd. A more comprehensive scheme was devised by George Bedson in the following year (British Patent 1935, 1862) for a continuous rod and bar mill, comprising of sixteen two-high stands arranged in a line with alternate stands mounted horizontally and vertically to work the bars on all four sides. The rolls were driven through gears arranged to increase progressively the
speed of rotation in successive stands and so accommodate the increasing length of
the stock generated by each rolling pass. A mill of this type was installed in 1862 at
the Bradford Iron Works in Manchester. Production delays caused by cobbles and
other problems deterred other companies from adopting the new style of mill, but
by 1867 two continuous mills were in operation at the Dowlais works.¹²

The Belgium looping mill for rod production was also introduced into Britain in
the early 1860s. This consisted of several three-high stands mounted side by side
and driven by a common shaft. The front end of the rod, emerging from the first
pass, was caught in a pair of tongs by an operator who then pivoted through 180°
to insert it into the pass in the next rolling stand. This operation was repeated until
the rod emerged from the last stand and it was then fed to a coiling machine.

Very few continuous mills had been commissioned in Britain by the end of the
nineteenth century. Most works continued to use two or three high cross-country
mills and the manipulation of the heavier ingots was simplified by the introduction
of the reversing mill drives. J. G. N. Alleyne attempted to operate a reversing
rolling mill in 1861, using two steam engines which rotated in opposite directions
and connected alternately to the rolls through mechanical clutches. The design
proved to be too complex for general use, but four years later John Ramsbottom
operated the first successful reversing mill at the Crewe workshops of the London
and North Western Railway. A railway engine mounted on blocks was used to pro-
vide the drive. A reversing mill driven by a stationary engine was in use by 1869 at
Siemen's Landore works and other companies then quickly adopted the design. It
was still normal practice in the early 1860s to forge the ingots or balls of malleable
iron to a size that could be accommodated in the rolls, but a three-high blooming
mill had been installed in 1856 at the Dowlais works. With the introduction also of
the reversing mill drive there was a general trend to use rolls of larger diameter to
accommodate larger metal cross-sections in the initial rolling passes and reduce the
need for the preliminary forging. More powerful drive engines also allowed
marked increases in the speed of rolling.

The combined effect of these developments increased markedly the throughputs
from the larger rolling mills. In the twelve years from 1869 to 1881 the average
weekly production from rail rolling mills was raised from 500–600 tons to over
2000 tons, while the fuel consumption per ton of metal rolled had decreased to no
more than half the quantity that had been consumed in 1869.⁴ In marked contrast,
the average weekly output from the mills producing wrought iron bar and sheet
was still only about 50 tons. The number of rolling mills used by the iron trade had
increased during the century almost as rapidly as the growth in wrought iron
output. By 1884, when the output had just passed the peak, 875 mills were distrib-
uted between 259 wrought iron works.⁸⁰

The energy consumed in reheating ingots prior to rolling was markedly reduced
when John Gjers designed the first ingot soaking pits. In an extension of the prin-
ciple first propounded by Henry Bessemer in his Cheltenham address to the British
Association, Gjers showed that an ingot could be rolled without supplementary
heating if it was removed from the mould and placed in a refractory-lined pit to
homogenise the temperature when the shell had solidified but the core was still molten. The first soaking pits were installed in 1882 at the Darlington Iron Company. The development was soon widely adopted for, in addition to the energy saving, it facilitated the rolling of large ingots, which could be moved more easily by an overhead crane when mounted vertically in a pit than when they were laid horizontally on the refractory hearth of a reheating furnace. As the number of ingots produced from one heat of steel increased, however, it became increasingly difficult to ensure that all the ingots had been removed from the soaking pits and rolled to size before the temperature of the metal had fallen too far. Supplementary heating eventually had to be incorporated in the soaking pits, but the energy consumption was still low when compared with the reheating of cold ingots in a furnace.

The production of ferrous forgings increased rapidly following the introduction of the steam hammer, but the relatively shallow depth of deformation that could be obtained by this means limited the maximum cross-section of metal that could be forged satisfactorily. The steam press, which had been developed by Joseph Whitworth for the production of armaments and gave a deeper penetration of the work front, began to find more widespread application from the early 1860s to overcome this limitation. The Sheffield firm of John Brown and Company installed a 2000 ton press in 1863 for forging armour plate. Press capacities increased rapidly and particularly following the acceptance of open hearth steel by the Government as suitable for the manufacture of armaments. Charles Cammell and Company was using an 8000 ton press for this purpose by 1888.

The capacity of the plate mills continued to increase to meet the demand for armour plate both for home use and for export orders (Fig. 10). A mill capable of rolling plate up to 100 mm thick was installed in 1856, during the Crimean war, at the Rotherham works of the Park Gate Iron and Steel Company. Six years later, John Brown and Company commissioned a mill to produce wrought iron armour plate up to 300 mm thick and in widths up to 2.5 m. Wrought iron plates of this thickness were needed to prevent penetration by the new design of pointed, steel tipped shells that were being made by Vickers Maxim and other suppliers.

Plate mills for the production of ship plate were installed at works on the North East coast and in Scotland when wrought iron and then steel were accepted for marine use. A plate mill was installed at the West Hartlepool Rolling Mills in 1855. Five companies in the area were producing wrought iron ship plate by 1865 (Ref. 18) and the number of mills increased when steelmaking was established in the Middlesbrough district. Production started later in Scotland and the first large plate mill at the Hallside works only started working in 1877, but growth was rapid in the following years.

Steel had almost entirely replaced wrought iron for ship plate by the end of the century. Steel was also being chosen in preference to wrought iron for use as beams and girders for constructional purposes. Two examples of the early adoption of steel for large structures are the Forth Bridge, completed in 1890 with the use of 54,160 tons of steel girders, and Blackpool Tower, built in 1894 with 2493 tons of steel.
4.2.2 Tubes and Pipes
Starting from a relatively low level, the requirement for tubes and pipes escalated rapidly during the early years of the nineteenth century. The initial demand arose mainly for boiler tubes and pipe work for stationary steam engines, but extended subsequently to pipe work for the new factory operations and then to the construction of railway locomotives. A new market also developed for pipes of large bore to convey water, gas and sewerage. Gas was first applied for street lighting in London in 1807.

Pipes and tubes were first produced by sand casting, but the process was limited to the production of short lengths. Longer tubes became available when the practice was developed for the butt and lap welding of wrought iron strip, using a gas flame. The first seamless tubes were made during the 1840s by rolling or drawing a cylindrical billet over a mandrel. Initially, a hole to accommodate the mandrel was drilled down the axis of the billet, but when the steam press was developed it was soon adopted for piercing the billets. Many new companies were formed around the midcentury to meet the growing demand for welded and drawn tubes. Two of these companies, Lloyd and Lloyd in Birmingham (opened 1859) and A. J. Stewart in Glasgow (opened 1862), bought out many of their competitors before the end of the century and then merged in 1903 to dominate the industry.

The Mannesmann Company in Germany patented a new process in 1885 for the production of seamless tubes. A hot cylindrical billet, up to 350 mm in diameter, was rotated between two barrel shaped rolls, which were mounted with their axes inclined to each other and to the axis of the billet. The deformation stresses opened up a central cavity in the spinning billet and the angular displacement caused the billet to advance over a pointed mandrel, which smoothed the surface of the cavity. The tube was then reduced to the cross-sectional dimensions and wall thickness required by deformation over a mandrel on a draw bench, with frequent interstage annealing treatments. This was a major advance in the production of seamless tubes. Friedrick Siemens, who had taken over the management of the Landore works when his brother, Sir William Siemens, died in 1883, acquired the British license for the process. The British Mannesmann Tube Company was formed in
1888 and took over part of the Landore works to make tubes from steel produced on the site.

4.2.3 Wire Drawing
Wrought iron wire was produced from the early years of the nineteenth century using Wortle plate dies. Steel wire was made from the midcentury onwards. The plate was a rectangular block of high carbon (about 1.0% C) crucible steel, which was usually about 300 mm long, 150–200 mm wide and 30 mm thick. A flat handle at one end was used to secure the block in position for wire drawing. Profiled holes, bored through the block, formed the drawing dies. Hot rolled rod was descaled and pickled to produce a clean surface before drawing through a succession of dies, with interstage annealing treatments, until the required cross-section was achieved. Tallow or soap was used as a lubricant.

The pass, or bearing, of the die eroded fairly rapidly and it was reshaped by hammering to partially close the hole then re-formed with a punch. Over a period of time, as the bearing continued to erode it was enlarged to draw a larger cross-section of wire. The durability of the dies was improved when the technique of hardening and tempering of steel was perfected and it then became possible to use hardened steel dies to make steel wire. A further improvement was obtained in the closing decades of the century by making the plates from a 1.0% C, 2.0% Cr steel after chromium had been adopted as an alloying element.

The wire trade was evidently profitable, for the construction and development of the Stocksbridge works of Samuel Fox and Company was originally financed, from 1848, by the manufacture of the first umbrella frames with iron ribs and, from 1855, by the production of finer wire for the frames of the Victorian crinoline dresses. The company introduced the shaping of wire by deformation between rolls with profiled passes to produce a U shaped cross-section and this wire was incorporated from 1854 in the lighter-weight Paragon umbrella frames.

The required cross-sectional area of wire could be specified and checked more precisely, following the introduction in 1884 of the Imperial Standard Wire Gauge. The wire industry by that time was located mainly in and around Warrington in South Lancashire, where over 40,000 tons of ferrous wire was produced annually.

4.3 Surface Coatings
3.3.1 Tin Plate
Tin plate manufacture was well established in Britain before the start of the nineteenth century. It was first made in 1665, but was only produced in small quantities until 1728, when rolling mills were introduced to replace hand hammering to make the wrought iron substrate. Few changes were made to the processing route before 1800 and only relatively minor changes occurred during the first half of the nineteenth century. The tin coating was sometimes applied to wrought iron sheet which had been made by puddling in coke-fired furnaces. The preferred base, however, was a hematite pig iron that had been pre-treated in a charcoal finery and then pud-
The iron plates were pack-rolled with doubling and re-doubling to produce eight sheets in a pack. The sheets were then separated and trimmed to size, typically 300–400 mm by 250–500 mm. The trimming operation was simplified when the guillotine shear was introduced in the 1820's, but the laborious process of separating the sheets from a rolled pack was not mechanised until the 1890s. After descaling and pickling, the sheets were placed in a stack, covered with inverted iron boxes which were sealed with sand to prevent re-oxidation, and annealed for about 10 hours. When cold rolling was introduced to produce the final gauge with a smoother surface finish, the black plates were re-annealed at a lower temperature after cold rolling and before a final pickling treatment. From 1806, a sulphuric acid pickling solution replaced the traditional barley meal and vinegar treatment and was also used for the descaling of hot rolled plates from midcentury. Mechanically operated pickling cradles came into use in 1874 and hydrochloric acid pickling solutions started to be used at about the same time.

After washing to remove all traces of acid, the plates were tinned by successive immersion in a row of five cast iron pots. The first pot, containing molten palm oil or tallow, removed any residual moisture from the surface and pre-heated the metal. This was followed by the 'tin man's pot' containing molten tin covered by a layer of grease. The purity of the tin was higher in the third pot and higher again in the fourth pot to give a high-quality surface to the coated sheet. The sheets were then placed vertically in a rack in the last grease pot to allow the excess tin to drain from the surface, the thickness of the residual coating decreasing as the holding time was extended. The latter stage was mechanised in the 1860s when, in separate developments, E. Morwood at Llanelly and T. Saunders at Cookley incorporated driven rolls in the final grease pot to regulate the thickness of the coating. Tin coated sheet, using a tin-lead alloy containing between 33 and 67% tin, was made by a similar procedure.

Although it was labour intensive, the five-pot arrangement could produce about three boxes, each containing 50 kg of tin plate, per hour. The output was almost doubled with two changes that were introduced during the 1880s. A mechanical tinning line, in which the metal sheet was drawn by rollers through a tin bath, replaced the individual pots and zinc chloride was used as a flux to replace the initial immersion in palm oil. The flux was constrained by a rectangular frame to float on the molten tin at the entry end and a similar arrangement limited the spread of the palm oil at the discharge end. Long lengths of metal sheet could be readily plated with this set up and one report recorded the tin coating of a plate 150 mm wide and 45 m long. Electrolytic tinning was first practiced in the 1890s, but only a very small share of the market had been taken over by the end of the century.

Attempts to substitute steel for wrought iron black plate initially made very slow progress. Philips and Smith of Llanelly successfully tinned sheet that had been rolled from one of the earliest Bessemer melts made at Baxter House in 1856. They
took out a license to operate the converter process but this was subsequently cancelled, together with all the other early licenses, when the steel was found to be too brittle for general use. Further attempts were made to apply converter steel for tin plate production after the Bessemer works was opened in Sheffield, but the general verdict was not encouraging. The major breakthrough in the use of steel for this application came after the opening of the Landore works. Open hearth steel proved to perform very satisfactorily as the substrate and it had almost completely replaced wrought iron black plate by 1890.

The industry was located primarily in Monmouthshire and the Swansea area of South Wales, where nine works were producing tin plate in 1800. The number of works had increased to thirty-four by 1850, fifty-nine by 1870 and ninety-six by 1885. The annual output was then 360,000 tons, of which 106,998 tons was made in the Swansea district. A flourishing export market had been developed and roughly half the output was exported. Almost half of this was shipped to the USA. The industry was just recovering from a recent recession in Britain when it suffered a severe blow from the imposition in the 1891 McKinley Tariff Act of a levy of £10 per ton of tin plate imported into the USA. Exports to other countries took up some of the spare capacity but, by the end of the century, cheaper black plate was being imported into Britain from America. The number of rolling mills in South Wales producing black plate fell in consequence from a peak of 519 in 1890 to 308 in 1896 (Ref. 12) and there was a steady decline also in the number of manufacturers applying tin coatings.

4.3.2 Galvanising
A zinc coating was applied to an iron sheet in Italy in 1772, but the first commercial process was patented in 1837 in France. Henry William Crawford took out a British patent for the method (British Patent 7355, 1837) and a galvanising works was opened in 1838 in Southwark in South London. After removal of any surface oxides and scale by pickling, the metal was simply immersed in a bath of molten zinc, which was protected from oxidation by a floating layer of sal ammoniac.

By midcentury several firms were applying zinc coatings to wrought iron sheet, wire, tubes and other fabricated components. Demand thereafter grew rapidly and particularly during the last two decades when the manufacture of steel sheet and tube was also increasing rapidly. The Panteg and Pontypool works of Richard Thomas and Company began the production of galvanised sheets in 1895. John Summers started galvanising on a very small scale in 1894 at the Globe Works in Manchester. He then built the Shotton Works in North Wales to cope with the rapid growth in orders for galvanised and corrugated sheet. The plant produced 40,000 tons of coated products in 1898. Over 100 hot dip galvanising lines had been installed in Britain by the end of the century and progress was beginning to be made with the development of electro-galvanising.
5. PHYSICAL METALLURGY

Published accounts concerning the nineteenth century ferrous industries tend to concentrate on the technological developments which accompanied the enormous growth in production. Little attention was paid to the early applications of scientific methods to the study of the metal and to the manufacturing route with the aim of exercising closer control over the mechanical and physical properties exhibited by the products. Specifications for metals were crude at the start of the nineteenth century. As noted earlier, reliable methods for chemical analysis had not been developed. Ferrous metals were differentiated for use by observation of the appearance of a fracture surface and by assessment of properties such as the hot ductility and the brittleness at ambient temperature. Yet, in using these simple methods alone, a skilled operator could classify a cast iron into one of eight grades, ranging from a ductile gray, number 1 iron, through mottled irons, numbers 3–6, to a hard and brittle number 8 white cast iron.

A firmer basis for classification was established after C. J. B. Karsten demonstrated that the carbon content was the principle difference between wrought iron, cast iron and steel. The formation of solid solutions was not recognised until the century had almost drawn to a close and the elements were assumed to exist only in molecular form when they were present in a solid. But in 1827, Karsten deduced that carbon in iron could exist also as an iron carbide. He investigated the effect of the carbon content on the hardenability of steel and was the first to show that it was necessary to raise the cooling rate as the carbon content decreased in order to fully harden a ‘soft’ steel. The upper limit of the carbon content at which wrought iron was assumed to change into steel was not clearly defined. A distinction between the two was normally made on the basis that wrought iron could not be hardened by quenching but all steels could be hardened. This arbitrary division was maintained for several decades. As late as 1884 it was stated that ‘it is usual to call all puddled bars which cannot be hardened in water bar iron, and all those which can puddled steel. This dividing line falls somewhere near a mixture containing 0.5% carbon’. The division between steel and cast iron was usually set at 1.5% carbon.

5.1 Alloy Steels

Although Mendeleef’s periodic table of the elements was not published until 1871, most of the elements had been identified by the start of the nineteenth century. With the exception of the basic metals that had been in use for several centuries, however, commercial methods had not been devised for the bulk production of the metallic elements. Consequently, as the relatively undemanding engineering requirements for ferrous metals could be satisfied by the straight forward production of iron and steel from iron ore and scrap metal, there was little incentive for the study of the effects produced by the presence of other elements in the material. This attitude persisted until after the midcentury, although sporadic attempts were made to evaluate the effects produced by alloy additions.
The first systematic study was undertaken during the 1820s by Michael Faraday and James Stewart, working at the Royal Institution in London. The initial objectives were to produce a superior grade of Wootz metal and better tool steels. Crucible melts of the more promising compositions were made at the Sheffield works of Sanderson Brothers, using mixtures sent by stagecoach from London and the forged ingots were returned to the Royal Institution for evaluation. Rhodium additions were reported to improve the cutting edge of cutthroat razors and similar items, while good mirrors could be made from an alloy containing 50% platinum. Additions of copper and tin were considered to be of doubtful value, but improvements in strength and corrosion resistance were claimed to result from the addition of up to 3% of chromium or nickel. The best improvements were claimed to result from the addition of silver, gold and other precious metals, but the steel-makers did not regard these alloys as economic propositions and the optimistic claims of the investigators were largely ignored.

The first commercially successful alloy steel produced in Britain was invented by Robert Forester Mushet. In a 12 year period starting in 1856, he obtained more than fifty patents concerning the manufacture of iron and steel, including one that was referred to earlier in this chapter, for the addition of a manganese alloy to deoxidise Bessemer steel melts. Some of the patents described alloying steel with chromium, titanium and tungsten. He was particularly enthusiastic about the benefits resulting from titanium additions, taking out thirteen patents between 1859 and 1861 relating to the production of the element and methods by which it could be incorporated in steel melts. His works in the Forest of Dean was renamed as the Titanic Steel Works. Unfortunately for his investigations, an accurate method had not been devised for determining the titanium content of the steels he produced. When it was added to crucible melts the recovery of the element in the solidified steel was undoubtedly low and very variable and the properties varied correspondingly.

Mushet's first real success was achieved in 1868 with the addition of tungsten to steel. The tungsten ore, wolframite, was added to a melt of Swedish white iron to produce an alloy containing 8–9%W, 1.8–2.0%C and 1.0–1.5%Mn. The composition was modified slightly to include up to 1.0%Cr in the following year. It was marketed initially as Robert Mushet Special Steel. When it was realised that it could be hardened simply by air cooling, however, it was renamed Self Hard Steel. Mushet had committed all his financial assets to the development work, but the costs were not recovered sufficiently rapidly from the sale of the steel and in 1870 the Titanic Company went into liquidation. The high speed steel patents were then taken over by the Sheffield firm of Samuel Osborn and Company, who modified slightly the composition to improve the deformability. Considerable care was required to avoid the formation of cracks during the hot working of the original alloys so a leaner alloy was launched in 1878, of nominal composition 6.0W–2.0C–2.0Mn–1.0Si–0.5Cr, which exhibited better forgeability.

The first commercial chromium steel was made by Julius Bauer, who founded the Chrome Steel Company in 1870 in the USA, but Berthier in Germany had already claimed that chromium additions made steel less magnetic and more resist-
ant than plain carbon steels to dissolution in acids. John Brown and Company started to produce chromium steels in 1871 at the Atlas works in Sheffield. The only ferro-chromium available had a high carbon content and consequently the first chromium steels also had high carbon contents. This resulted in poor workability, but the alloys exhibited high strength and hardness. They were quickly adopted for the manufacture of drills, cutting tools, safes and other applications for which high strength and hardness were required.

Robert Abbott Hadfield was provided with a laboratory in 1874 for his own use in his father's works and he embarked on a systematic study of the effects obtained from the addition to steel of single and multiple alloy elements. Aware of the damage that had been caused when a ceramic grinding wheel had disintegrated during use, he attempted to make grinding wheels from a steel with a high manganese and silicon content. Wheels made from a crucible steel containing 3.96%Si, 7.4%Mn and 1.5%C were found to be very hard but almost as brittle as a ceramic wheel. This led him on to a more intensive study of the effects produced when alloy elements were added individually.

Starting in 1882, he made an examination of the effects created by the addition to steel of 1.0–20%Mn. A problem similar to the earlier limitation on the study of chromium additions was encountered, for the only ferro-manganese then available had a high carbon content. Consequently, the carbon concentration in the alloy steels increased with the amount of manganese added and exceeded 1.0% when 12% of manganese was present. Pearlitic steels containing between 1.0 and 1.5% manganese were found to exhibit increased strength and toughness, but alloys containing between 3.0 and 7.0% manganese were very brittle. No explanation was offered for the discovery that alloys containing more than 10% manganese were very soft and remained soft after water quenching from a high temperature, but they could strip the teeth from a file. The high strength, toughness and wear resistance that was achieved at the relatively low cost for the ferro-alloy addition resulted in a strong demand for the latter alloy. Hadfield's Manganese Steel containing 12–14% Mn was soon widely applied in both cast and wrought forms. The steel was found to be non-magnetic and it was suggested that 'an approximate idea of the amount of manganese in this steel can be found by passing a strong magnet over the specimens'.

The results obtained from Hadfield's investigation into steels alloyed with silicon were initially regarded as unattractive. The influence of silicon on the graphitisation of cast irons was then widely recognised but, in marked contrast to the effect of manganese, Hadfield showed that the solubility of carbon in ferro-silicon and also in steel decreased as the silicon content was raised. Alloys containing up to 6% silicon could be cast and forged with care if the carbon content was low, but they could not be hardened by quenching. Hadfield concluded his account of his work on these alloys with the statement that 'the author does not claim that there is any field for the employment of ... a high silicon steel'. Applications of silicon steel for springs and for ship plate manufacture were being investigated before the end of the century, but the first silicon iron transformer sheets were not produced until 1903.
Several workers studied the use of nickel as an alloy element, following the initial investigation by Faraday, but J. Riley working in 1889 at the Steel Company of Scotland was responsible for the first successful development. His studies were aided by the start in the previous year of production by the Mond process of metallic nickel free from contamination with carbon, sulphur and phosphorus. Low carbon steels containing 3.5–5.0% nickel were found to exhibit a significant increase in strength and ductility and increased resistance to corrosion, when compared with unalloyed steels with the same carbon content. The strength and toughness were increased by a quench and temper treatment and the alloys so treated were soon adopted for use as armour plate. It was used also for boiler shells, rifles and gun forgings. Steels containing up to 5% nickel could be machined with moderate ease, but it was found that they were too hard to machine when 10% nickel was present. The hardness increased with concentrations up to about 20% nickel, but Riley then found a progressive decrease in hardness and the steel became more ductile when the concentration was further increased. The similarity to the behaviour of steels with a high manganese content was not recognised at that time. Later work showed that an alloy containing 25% nickel was non-rusting and showed 'perhaps all the qualities of German silver together with greater strength'.

5.2 Metallography

The discipline of metallography was a late nineteenth century development. Henry Clifton Sorby, a Sheffield geologist, was the first person to make a detailed examination of metals under the microscope. His seminal paper, describing the changes in the microstructure brought about by changes in the composition and processing parameters was presented to a meeting of the British Association in 1864. It evoked little interest and he reverted to the study of geological specimens. A. Martens began to study metals under the microscope in 1873 and F. Osmond followed suite seven years later in Paris. The reports of their work stimulated Sorby to resume his metallurgical studies. His earlier paper was updated, presented to a meeting of the Iron and Steel Institute in 1885 and was eventually published two years later. The early work only used magnifications up to $\times 200$, but he was able to resolve the structure of the 'peary constituent' when the magnification was increased to $\times 600$. He had earlier identified this constituent as alternate 'layers of carbon-free iron and the intensely hard substance seen so well in blister iron'. On the basis of his later observations he postulated that the separation into two constituents was 'suppressed to give great hardness and strength on quenching'. Contrary to popular opinion at the time, he showed that the structure was granular and not amorphous. The process of recrystallisation was observed during hot working and during annealing.

R. Akerman had proposed earlier that carbon in iron could exist either as graphite or as combined carbon. He claimed that the latter phase normally existed as 'cement carbon' and was transformed into 'hardening carbon' by quenching from a red heat. Hardening carbon could be transformed back into cement carbon by reheating followed by slow cooling.
The measurement of elevated temperatures was very crude and unreliable before 1870. It usually relied upon crude techniques such as the matching of the colour of some artifact (e.g. a piece of orange peel) with the colour exhibited by the hot metal. When C. W. Siemens invented the platinum resistance thermometer in 1871 he was able to demonstrate the wide error bands that applied when temperatures were assessed by the previous methods. A very significant advance in accurate high temperature measurement was achieved in 1887 when Le Chatelier introduced the platinum–platinum/10% rhodium thermocouple. F. Osmond almost immediately applied this to the thermal analysis of iron and steel. Three thermal arrest points had been identified by 1890, which he labelled $A_1$, $A_2$, and $A_3$, and, after observing recalcitrance during cooling, he applied the subscripts of 'c' for chauffage (heating) and 'r' for refroidisement (cooling). He noted that the temperature of the $A_3$ arrest was gradually depressed on slow cooling from a maximum of 885°C as the carbon content was increased, merging with the $A_2$ point in 'medium' carbon steel and with the $A_1$ point in 'hard' steel. The $A_1$ arrest temperature was reported to increase from 660°C in electrolytic iron to 695°C in white cast iron. No values were given for the $A_c$ arrest temperatures. The temperatures attributed to the melting points of the pure metals and compounds used in the calibration of the thermocouples in this and in similar investigations undertaken in the late nineteenth century often differed significantly from the values that are accepted today and this may account for the discrepancies.

Through reference to earlier work, which had been published by J. A. Brinell, Osmond attributed the $A_1$ arrest to the transformation of the carbon in the steel from the 'hardening carbon' state into cement carbon. In the initial interpretation, iron was assumed to exist in a beta form from above $A_3$ and the $A_2$ arrest was interpreted as the end of the transformation from the beta to the alpha form. A third allotropic modification was introduced in a later report and it was then postulated that iron transformed from a high temperature gamma form into the beta phase at the $A_3$ temperature. He noted subsequently that the $A_2$ temperature was not changed significantly by variations in the heating and cooling rate and he ascribed the arrest correctly to a magnetic/non-magnetic transformation. The hardening that resulted from water quenching was attributed to the retention of the beta structure at room temperature, but it was found that carbon was required to stabilise the beta form and this was accepted as the reason why malleable iron could not be hardened by quenching. Osmond postulated also that iron reverted to the alpha form during tempering as the carbon separated to form the cement carbon.

A dispute then arose between proponents of alternative explanations for the changes that occurred at the arrest points and for the mechanism of hardening. J. O. Arnold supported a group which maintained that the $A_1$ point marked the transition of iron from a crystalline to a plastic state. Quench hardening was attributed to the retention of carbon in the form of an iron carbide of composition Fe$_{24}$C. He had earlier deduced that Fe$_{24}$C formed the hard component of the pearlite constituent, based on a derived eutectoid carbon content of 0.89%. The interpretations were further confused when E. J. Ball reported the detection of a fourth arrest point.
in a 0.12% carbon steel, at a bright yellow heat, which was estimated to be about 1300°C. A consensus on the transformation mechanisms had not been reached by the end of the century.

A tentative form of the eutectoid region of the iron–carbon phase diagram was produced in 1898 (Fig. 11). This diagram correlated with data presented by J. E. Stead describing the effects of time at temperature and heating and cooling rates on the temperatures required for full annealing and for the tempering of plain carbon steels as a function of the carbon contents. Stead described also the changes in the crystallographic appearance caused by annealing and by tempering. Factors were identified that influenced the transition from an intercrystalline to a transcryalline fracture. He also noted the development of a crystallographic texture (i.e. a preferred orientation) when low carbon steels which had been cold worked were viewed with a microscope using polarised light. Conditions were also described, that gave rise to the formation of divorced pearlite and the formation of grain boundary carbide films when steels with very low carbon contents were cooled slowly after hot working or annealing. Roberts Austin produced a liquidus diagram for iron–carbon alloys in 1899 (Ref. 101) and Rozeboom derived the complete phase diagram in the following year.

Osborn and Arnold both studied the effects produced by the addition of alloy elements on the hardenability of iron and steel. In agreement with an earlier proposal from Roberts Austin, Osborn claimed that the $A_3$ temperature was lowered

Fig. 11 The eutectoid region of the iron–carbon phase diagram, 1898 (J. Iron Steel Inst., 1898 (1), Page 265, Fig 3).
and the hardenability was increased by additions of carbon, boron, manganese, nickel and copper, all of which were attributed atomic volumes smaller than that of iron. Chromium, tungsten silicon, phosphorus and sulphur, with larger atomic volumes, were reported to raise the \( A_3 \) temperature and decrease the hardenability, although the effects of tungsten and sulphur were very small and inconsistent. When sufficient nickel or manganese was added 'the critical point could be lowered below 0\(^\circ\)C on cooling'.\(^\text{95}\) In contrast, Arnold claimed that silicon, aluminium and phosphorus eliminated entirely the \( A_3 \) arrest and tungsten diminished its intensity, whereas manganese, chromium, nickel and copper lowered the \( A_3 \) temperature below the \( A_2 \) point.

Several investigators sought to correlate changes in composition, heat treatment and microstructure with variations in the properties determined by tensile and bend tests. The work was beginning to bear fruit by the end of the century and the development of specific properties in a product was changing rapidly from trial and error or rule of thumb methods towards a more rigorous scientific basis.

The description of the micro-constituents of iron and steel was simplified after 1888, when H. M. Howe introduced the nomenclature of ferrite, pearlite and cementite. The list was extended when Osmond added martensite, sorbite and troostite. The austenite phase was introduced at a later date. But confusion still reigned. As late as 1898, a statement was published\(^\text{99}\) that

\[
\text{at present nothing whatsoever is known as to whether martensite, together with austenite, occur immediately below the melting point, or whether separation of the cementite takes place at the same time as the graphite, or not till after this.}
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The foundations of metallography had been laid, but much remained to be done to develop it into a universal tool. It was regarded as primarily an academic exercise and no works had started to employ metallographers at the close of the nineteenth century.

### 6. REFERENCES

CHAPTER 2

Technological Developments in Iron and Steel during the Twentieth Century

T. GLADMAN AND F. B. PICKERING

1. INTRODUCTION

The twentieth century has seen the most rapid advances in science and technology in recorded history. Every technology has changed, from what in many cases was an art to an exact science and to an extent virtually inconceivable in 1900. Never is this more so than in the case of iron and steel. To document all the developments, which have occurred in the last 100 years, is a forbidding task and this chapter can do no more than select various aspects of the subject which are idiosyncratic to the authors. It is sometimes impossible to find a true, developmental sequence as many different aspects were taking place simultaneously. Equally, the sequence described by any given narrator is influenced often by the desire to present a logical progress when none may actually exist. Also, the need to preserve commercial advantage and to protect advances by patenting, often prematurely, can obscure the true developmental path. Hence, a technological history must never be viewed as a technical or scientific textbook.

The workers in the field were not always aware of the significance of their observations in the overall scientific and technological scenario. This has become especially the case owing to the explosion in the technical literature and its fragmentation into a myriad specialist fields. The inability to be familiar nowadays with the whole literature of a subject often leads to the reliance on the use of computer indices which often go back less than twenty years. Hence, much of the earlier work, which was highly relevant, may easily be overlooked. The confusion created by the conjunction of all the above problems can readily be appreciated, and is aptly illustrated by attempts to define precisely the history of the development of alloy steels and stainless steels in particular.

The twentieth century has also seen wide ranging changes in society and the methods of working. The first half of the century saw two devastating world wars and, possibly, an even more devastating economic depression in 1929–1935. But the second half of the century has also seen a second, or maybe continuing, revolution,
which has surpassed the changes brought about by the first industrial revolution. This was initiated by the invention of the microchip in 1958–1959 and its application to automation and process control, coupled with immense changes in the storage and distribution of information. This has resulted in fundamental adjustments to the everyday life of workers in manufacturing and in the service industries.

At this point it is instructive to examine how crude steel output has varied throughout the twentieth century (Fig. 1). In 1900, less than 30 million tonnes of steel were produced and by the start of the First World War this had increased to about 70 million tonnes. Some 20 million tonnes of this increase occurred in the USA, the remaining similar amount being produced in Europe and particularly in Germany, partly as a result of militarisation and the arms race, which this engendered. The depression of 1921 caused a major decrease in steel production to about 45 million tonnes, but thereafter for some 10 years production increased steadily to about 120 million tonnes in 1930, of which about half was produced in the USA. The worldwide depression of the early 1930s more than halved steel production to some 50 million tonnes in 1932, with production in the USA plummeting to only 15 million tonnes compared with 63 million tonnes in 1929.

Recovery after the depression, coupled with rearmament in the late 1930s increased world steel production to about 140 million tonnes in 1939, but even during the Second World War (1939–1945), production showed only a modest increase to 150 million tonnes in 1944. The next two years saw a further sharp decline to 110 million tonnes per year, a consequence of the destruction of European and Japanese steel plants. Thereafter, and especially from 1950 to 1980, there was an unprecedented rate of growth in production, amounting to almost 20

![Fig. 1 World steel production.](image-url)
million tonnes annually, so that by 1980 the output was 715 million tonnes. This was associated with new and improved plants coming on stream in Europe after the war and by the development of the steel industries in Japan and other Eastern countries. The established industrial countries of the West progressively lost their market share. The requirements of a booming world economy drove this phenomenal increase, which was met by the opening of many new plants, the restructuring of the industry to achieve greater efficiency and output, and by no means least by the development of improved and computer controlled processes. Between 1950 and 1970 the average growth rate in production was about 5% per year in the Western world, but since 1970, this growth rate has fallen to less than 1% per year. Whilst steel production very slowly continued to increase, reaching 798 million tonnes in 1997, clearly a degree of saturation has been reached and overall there has been some overcapacity which has resulted in rationalisation and plant closures. Nevertheless it should be appreciated that more steel is currently produced in Britain than at the height of the Second World War.

Figure 1 illustrates two interesting features. First, major world wars do not result in a sudden surge in steel production; rather there is a switch in production from civilian to military usage. The main effect is in the process of rearmament, which usually precedes war. This illustrates the relatively long lead time required to increase steel production significantly because of the need to construct new plants or replace an existing plant. Second, and even more importantly, it is quite clear that steel production is driven by increased economic activity, as shown by the major effects of depressions and the huge increase in absolute terms produced by the prolonged period of economic boom from 1950 to about 1980. The long lead time, previously mentioned, can be expected to produce over optimism in the prediction of steel requirements and the tendency for overcapacity is now apparent. But it is not to be concluded that steel is in decline; the continuing increase in world population and the demand for steel by this burgeoning population will ensure, at least for the foreseeable future, that production will still continue to grow albeit at a much decreased rate. It can fairly confidently be concluded that, despite the many predictions of the demise of steel, such views are deluded and indeed fundamentally flawed. The reasons for this are simple: the huge reserves of economically viable ores and the ease with which these are reduced to the metallic state, and the recyclability of the metal. Indeed, such dire prognostications of the demise of steel and its replacement by the ‘sunrise’ materials, are not new. In 1910, Henry Marion Howe was addressing similar predictions but based then upon the availability of iron ore.

2. A VIEW OF AD2000 FROM THE PERSPECTIVE OF AD1900

In order to set the scene, it is necessary to review the technology available around 1900 and to outline briefly the technological changes in the last 100 years. In reviewing the literature of 1900, today’s metallurgist has difficulty in divorcing himself
from the knowledge and understanding which has accumulated in the twentieth century. Papers written around 1900 are often difficult to understand, not only because of the limited knowledge then available, but also owing to the unfamiliar terminology and not least the rather philosophical, and sometimes highly speculative, style of writing. Consequently, a more rounded overall view may sometimes be obtained from books written for didactic purposes in the first two decades of the twentieth century. The difficulty of putting oneself into the position of a metallurgist in 1900 is great, but it may be interesting to consider what would be the major impressions of a 1900 metallurgist, could he return and view the steel industry in 2000.

It is necessary to understand that he would probably have received an education based largely on classical studies, leavened by the science of chemistry and some mathematics. Indeed metallurgists in 1900, and for many years afterwards, were essentially metallurgical chemists. He would also have a more than superficial knowledge of the major items of plant used in the processes of manufacture and in the investigational techniques available to him.

Only a few of what may be his major impressions can be suggested, but possibly his greatest surprise would be a more than twenty-five fold increase in steel production. He would look in vain for most of the familiar names of steelmaking companies of his day, but be quite reconciled to the progressive trend for company mergers and the economies of scale that such a large increase in steel production would entail. He would be aware of the trends for mergers, trusts and corporations in the USA and Europe; indeed the merger between Carnegie Steel and Federal Steel to form the United States Steel Corporation took place in 1901.

Had the 1900 metallurgist visited a large modern integrated iron and steel plant in 2000 he would have been impressed by the scale of production and especially the rate of production. For example, a modern blast furnace in 2000 can produce some 3 million tonnes of pig iron a year compared with about 150,000–200,000 tonnes per year in 1900. Equally, the rate of open hearth steelmaking in 1900 was about 10 tonnes per hour (which had not increased greatly even by 1950) and that of Bessemer steelmaking some 50 tonnes per hour, compared with 600 tonnes per hour for a modern BOS furnace. Coupled with this would be his astonishment at the virtual absence of operatives on the shop floor, since he could not have predicted the impact of the computer on the operation and control of processes.

He would be familiar with the blast furnace and perhaps rather surprised that this was still used for iron production in 2000, because he would be aware of the opening up of the American oil and gas fields and the potential for direct reduction of iron ore by hydrocarbons. Equally he would be surprised to observe that the flourishing ore mines in the UK in his day no longer operated, with much higher quality ore being imported in the ore carriers of several hundred thousand tonnes deadweight; the normal cargo vessel in 1900 was only a few thousand tonnes. This had led to the shift of large integrated plant to coastal sites with special facilities for berthing large ore carriers. Although aware of the possibility of ore sintering, the 1900 metallurgist would be surprised at 100% sinter blast furnace burdens.
In steelmaking, he may have been saddened by the demise of the open hearth process and no doubt highly intrigued by the spectacular developments in the Bessemer type, or pneumatic, processes culminating in the modern BOS furnace of up to 350 tonnes or more capacity. But he might not have been surprised by the greatly expanded use of electric steelmaking, as electric arc furnaces were just becoming available in his day, albeit of only a few tonnes capacity. The first commercial use of the Heroult arc furnace was in France in 1899–1900 and by 1910 electric furnaces of 15 tonnes capacity were operating in the USA. The 1900 metallurgist would be well aware of the potential for electric steelmaking resulting from his knowledge of the development of the electricity generating industry, but he possibly would not have been aware of the potential for induction melting, the first large (a few tonnes) induction furnaces not coming into use until well into the second decade of the twentieth century. No doubt he would have been surprised to find that steelmaking, as he knew it, was not carried out in the steelmaking furnace, which is now only used as a melting unit. He could not have forseen the advent of the many secondary steelmaking processes and the use of vacuum processing, which were more than 50 years in the future.

As his major interest was probably in chemical analysis, he would have looked in vain for the chemical laboratory, and have been surprised to realise that chemical analysis in 2000 was largely physics-based with spectroscopy (with which he would be slightly familiar) and the many X-ray and electron chemical analysis methods predominant. He would be excited and impressed by the speed of chemical analysis which enable the results to be fed back, virtually in real time, to the control of the steelmaking processes.

One of the major differences noted by the 1900 metallurgist would be the absence of ingot casting bays and he could hardly have been expected to forsee that today more than 95% of steel in the industrialised countries would be made by continuous casting. This would no doubt surprise him, although he would have been aware of the experiments on continuous casting in the second half of the nineteenth century. But he may have been surprised that near net shape casting and particularly strip casting had taken almost 150 years to develop after the patent on the process by Bessemer. Only in plants producing some specialised products would he have seen his familiar ingot technology.

The use of continuous casting has rendered the ingot cogging mill obsolete, a fact he would have noted with interest. The general rolling processes for billet, bar, rod, angles and sections would be familiar to our 1900 metallurgist but not the methods of continuous processing because in 1900 much rolling was manually operated. This severely limited not only the size of ingots that could be handled but also the throughput (a few hundred tonnes of coggd ingots per day). Hence, he would be fascinated to see modern continuous mills for rolling bar, rod and strip, and the coiling facilities now available. The primary aim of hot working in 1900 was to produce the required product form, to close up unsoundness in ingots and to achieve dimensional tolerances whilst producing a minimum of scrap. Temperature control was largely absent or rudimentary. Consequently, the 1900 metallurgist would find
it almost inconceivable that the rolling process should be controlled so as to produce the required microstructure for the necessary properties. Modern thermo-mechanical processing would be unfamiliar territory, as he had little detailed appreciation of structure-property relationships, although being aware that the lower the rolling/forging temperature the more ductile and tough was the steel. He was more concerned with the 'fibre' imparted as the segregations were elongated during hot working.

Hammer and press forging was well established in 1900, the ingot sizes being generally 4–5 tonnes, with larger ones being up to 10–15 tonnes. Some of the heaviest modern forgings of several hundred tonnes would be novel to him. The superiority of press forging over hammer forging was well recognised, and the sizes of press available in 1900 were probably some 1000 MN. The developments in forging and rolling to cope with larger sizes of ingot were largely driven by the heavy gun and armour plate requirements of the Dreadnought type battleship, which were designed and built only in the years following 1900. Most of the standard tube and pipe making processes were available in 1900, including the hot rolling of pierced billets over a mandrel and the use of the pilgering process. Cold drawing of tubes was also practised and many of the basic processes today would be familiar to the 1900 metallurgist, albeit with increased sophistication of equipment and control. Similarly, methods for producing welded tubes were not too dissimilar from those used today except that the welds were invariably pressure welded on a hot drawing bench instead of using a fusion welding technique with filler metal or autogenous welding. Much of the steel in 1900 was not considered suitable for fusion welding. However, hot formed tubes were cold drawn with interpass annealing. The size of some of the piping produced today would have surprised a metallurgist in 1900 and it would not have been possible for him to foresee the demands of the modern oil and gas industries.

Cold rolling of flat products had been practised for many years in 1900, for galvanised and tin coated products. Box annealing was invariably used which limited the size of sheet. The 1900 metallurgist could hardly have predicted the large continuous rolling and annealing plants now in operation as there was no demand from the automobile, packaging and white goods industries of the consumer society; the first Model T Ford was made in 1907. It is not possible to detail the differences in the wire drawing industries at this point. Suffice to say that the technology already had a long history in 1900, but only in the latter half of the nineteenth century had the so-called continuous drawing of wire been developed. Indeed barbed wire processing was patented in the mid 1870s and, as a cheap agricultural fencing, made possible the opening of the American West for agriculture and ranching. The telegraph in the second half of the nineteenth century, also greatly increased the demand for wire. But the 1900 metallurgist would be intrigued at the amount of ultra fine wire produced, for example tyre wire, as he could not have anticipated the high quality and freedom from non-metallic inclusions necessary for such a product.

Although aware of the potential of alloy steels and of the work of Mushet and
Hadfield, the metallurgist of 1900 could not have foreseen the immense developments and uses of sophisticated alloy steels at the end of the twentieth century. In 1900 less than 100,000 tonnes per year of alloy steels were produced, i.e. about 0.5% or less of steel production and this was mainly used for tool steels, armour and as electrical transformer steels consequent on the development of the electrical generating industry; the first silicon transformer steel was produced commercially just after 1900. Whilst chromium steels had been experimented upon in the 1880s, the development of stainless steel was still one or two decades in the future. Consequently he could not have foreseen the specialised plants devoted solely to stainless steel production, nor of course the developments in stainless, heat resistant or creep resisting steels. Certainly he could not have anticipated the potential for alloy steel development consequent upon the modern aeronautical and space industries, the first power flight not yet having occurred, nor the alloy steel developments for the electrical power generation industries.

3. IRON AND STEEL MANUFACTURE, CIRCA AD1900

The purpose of this section is to establish the state of the art in the manufacture of iron and steel at the turn of the century. A more detailed discussion occurs in the previous chapter. At this time, wrought iron was manufactured in significant quantities, as well as cast iron and steel. There are problems in describing the state of the art as many processes were in use at a given time and relatively novel processes may not have been adopted by all parts of such a fragmented industry as existed in 1900. This may be attributed partly to secrecy and partly to reluctance to change because of the capital invested in existing plants and processes or required for major developments.

3.1 Wrought Iron and the Bloomery

The manufacture of wrought iron by the bloomery process, whereby iron ore was reduced entirely in the solid state using charcoal, was introduced into the UK about 600BC. This process remained virtually unchanged until the introduction of the blast furnace process. The manufacture of iron in the blast furnace spread throughout the UK during the following centuries.

The change to pig iron manufacture produced a liquid product which could be cast into shaped moulds, but cast pig iron was very brittle. The pig iron therefore required refining and was heated in the 'finery' hearth with an excess of air, thus leaving a (solid) low carbon iron which was not dissimilar to wrought iron. Charcoal was the universal fuel until Abraham Darby successfully applied coke as the reductant in the blast furnace in 1709, thus freeing the manufacture of pig from the constraints of an ever limited charcoal supply. The finery was, however, still restricted to using charcoal owing to the intimate contact between fuel and iron, and the consequent pick-up of sulphur and other impurities from other fuels. This
restriction was removed in 1784 with the introduction of the puddling process by Henry Cort, which was based on the reverberatory principle. The iron was decarbureised and the low carbon product was removed as hot solid lumps of about 50 kg. The iron balls were then consolidated by hammering to give the typical slag-streaked wrought iron.

The major development of the early nineteenth century was the introduction of the 'wet puddling' process by Joseph Hall in 1816. Between heats, the furnace was fettled with an oxygen rich material which produced a 'pig-boil' when the carbon-rich pig iron came into contact with the oxygen-rich lining. The carbon content of the bath was reduced much more speedily than with Cort's original process, which became known as 'dry puddling'. 'Wet puddling' was so successful that it eventually replaced 'dry puddling' completely and was the standard process in 1900. This process was replaced by various steelmaking processes (Bessemer and open hearth).

In view of the limited life of the wrought iron industry, the twentieth century developments can be dealt with quite briefly. Early attempts to mechanise the process were unsuccessful and the then obvious decline of the industry precluded any extensive development work or heavy capital investment. The extent of the decline is shown in the following UK annual production tonnages:

<table>
<thead>
<tr>
<th>Year</th>
<th>Tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1870</td>
<td>3 million</td>
</tr>
<tr>
<td>1900</td>
<td>1 million</td>
</tr>
<tr>
<td>1930</td>
<td>0.1 million</td>
</tr>
</tbody>
</table>

It is ironic that Bessemer's attempts to find an improved way of producing wrought iron should lead to the demise of the wrought iron industry because of the better economic viability and superior engineering potential of steel.

### 3.2 Pig Iron and the Blast Furnace

Whilst the term iron may refer reasonably correctly to wrought iron, the terms pig iron and cast iron basically refer to iron-carbon alloys containing up to 3–4%C. The significance of the presence of the carbon is a dramatic lowering of the melting point from 1537°C for pure iron to 1160°C for eutectic Fe–C alloys. A direct consequence of this is the production of a completely liquid metal at the temperatures attained in stack-type furnaces. In 1509 the molten iron was used in a casting process to make cannon in Newbridge, Sussex, and also in 1543 at Buxted, East Sussex.

The early blast furnaces were stack-type furnaces with a height of about 2 metres and having a hearth diameter less than 1 m. The blast would be provided by water driven bellows, but the charcoal fuel was becoming scarce and expensive. Abraham Darby successfully carried out experiments on the use of coke at Coalbrookdale in 1709. Coal had been tried as the reductant much earlier but the impurities picked up, principally sulphur, produced iron of unusable quality. The use of coke
avoided such problems. Early blast furnace slags have been shown to contain lime in significant quantities, which is an effective flux for the alumino-silicate gangue.

The feedstock for the blast furnace thus comprised iron ore and other iron-bearing materials, limestone, coke and, of course, the air blast. Whilst the early blast furnaces used water-driven bellows and a cold blast, the blowing engines became increasingly powerful with the development of the steam engine, and later gas engines, the latter often using blast furnace gas as the fuel.

A significant development which occurred in the nineteenth century was the use of a hot blast. The first attempts at pre-heating the air blast started with Nielson in 1828, who used a completely separate fuel supply to give a modest pre-heat of about 350°C. The methods of blast pre-heating evolved over a period of some thirty years until the Cowper stove was introduced in 1860. This then was the state of the art at the turn of the century, the blast temperatures not uncommonly being maintained at 750–800°C.

Ore preparation in some form has been practised since the first discovery of iron and in this case involved the roasting of sulphur-bearing ores. Calcination was practised with carbonate ores. The ores could be calcined in open heaps where they were mixed with fine coal, ignited and allowed to burn progressively. Calcining in kilns was also practised extensively in the nineteenth century.

In the late nineteenth century, certain finely divided ores were mixed with lime or coal tar and pressed into bricks, but the practice was not used extensively. The ironmakers were very conscious of the cost of ore preparation and so at the end of the nineteenth century, the main treatment merely involved crushing and sizing. One of the most striking developments in blast furnaces was the size of the furnace itself. Many of the early furnaces of the seventeenth century were brick built and square in section with a fireclay lining. The hearth was about 1 m in diameter and such furnaces were capable of producing about 4 tonnes of iron per day. By 1900 furnaces were much larger, being capable of producing 50–100 tonnes per day. Some furnaces in America were able to take advantage of exceptionally rich ores of suitable size and, by hard driving, were able to produce up to 750 tonnes per day.

Many of the scaling-up processes were dependent upon activities in other fields; for example the invention of the steam engine. These engines were capable of supplying air at a much faster rate than any bellows system. The early furnaces were hand charged and open topped, but the increase in size and the sheer mass of material to be charged and the toxic gases led to the development of mechanical handling systems, such as storage bunkers, and skips for raising the burden to the furnace top, the latter being a significant feature as the heights of furnaces increased. Whilst the later charcoal blast furnaces were limited to some 7 m in height, blast furnaces at the end of the nineteenth century were of the order of 26 m.

A direct consequence of the sheer size of the furnace was a change in the method of construction to maintain structural integrity. The refractory materials themselves were also given attention, the early clay lining in the sixteenth and seventeenth centuries being replaced by firebrick. In the late nineteenth century, two developments were connected with the observed high wear rate of refractories in the bosh and
hearth. In the bosh, water-cooled metal containers were built into the walls to reduce the temperature and therefore the wear. In the hearth, carbon bricks were introduced and were made from a mixture of fine coke with about 20% tar, dried and fired in the absence of air. Although twice as expensive as good firebricks, they were infusible at blast furnace temperatures and were highly resistant to the action of both acid and basic slags. In the latter half of the nineteenth century, closed furnaces were introduced and in 1883, a double bell system was introduced that allowed materials to be charged without ever opening the system to the atmosphere, and this permitted a continuous blast. The closed system also assisted in the collection of the blast furnace gas. Following earlier attempts to suck the gases from open topped furnaces using a flue system, the use of a downcomer and dust catcher from a closed pressurised system operating at 7000 Pa (5 psi) was relatively simple and cleared the way for the introduction of gas engines just before 1900 in the USA and slightly later in the UK.

In an integrated iron and steel works, the molten iron from the blast furnace was later transported directly to the conversion furnace, the molten iron becoming an important feature of both Bessemer and open hearth steelmaking, whilst a pig casting machine dealt with any excess iron. The major developments in blast furnace ironmaking from their inception to the end of the nineteenth century are summarised in Table 1, and provides the base upon which twentieth century developments will be described.

### Table 1: Developments in blast furnace practice, AD1600–1900.

<table>
<thead>
<tr>
<th>Furnace size</th>
<th>Mediaeval</th>
<th>1900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hearth Diameter</td>
<td>&lt;1 m</td>
<td>3 m</td>
</tr>
<tr>
<td>Height</td>
<td>6 m</td>
<td>33 m</td>
</tr>
<tr>
<td>Tuyeres</td>
<td>2 of clay</td>
<td>6–7 water cooled copper jackets</td>
</tr>
<tr>
<td>Furnace refractories</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stack</td>
<td>Clay</td>
<td>Firebrick</td>
</tr>
<tr>
<td>Bosh</td>
<td>Clay</td>
<td>Water cooled firebrick</td>
</tr>
<tr>
<td>Hearth</td>
<td>Clay</td>
<td>Carbon bricks</td>
</tr>
<tr>
<td>Charging System</td>
<td>Open top</td>
<td>Double bell sealed system</td>
</tr>
<tr>
<td></td>
<td>Hand barrow</td>
<td>Hopper, tipping skips, inclines</td>
</tr>
<tr>
<td>Fuel</td>
<td>Charcoal</td>
<td>Coke</td>
</tr>
<tr>
<td>Air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blast</td>
<td>Water driven bellows</td>
<td>Steam engine/gas engine</td>
</tr>
<tr>
<td>Temperature</td>
<td>Cold</td>
<td>Hot 900°C</td>
</tr>
<tr>
<td>Pressure</td>
<td>Atmospheric</td>
<td>7000 kPa</td>
</tr>
<tr>
<td>Production Rate</td>
<td>4 t/day</td>
<td>50–100 t/day</td>
</tr>
</tbody>
</table>
3.3 Steel and the Steelmaking Processes

3.3.1 The Cementation and Crucible Processes
The first process to produce a steel-like product, as distinct from the very low carbon wrought iron, was the cementation process, in which wrought iron was placed in a crucible or chamber packed with carbonaceous materials and heated to a temperature of 1100–1200°C. The low carbon wrought iron absorbed carbon, with the carbon then diffusing into the iron. The process of cementation was introduced to South Yorkshire (via Newcastle) in 1672 and in 1716 a cementation furnace was built in Sheffield. The carbon content of the cemented steel could show variability between bars and even within a bar. The reaction between carbon and the oxygen in inclusions in the wrought iron caused the formation of carbon monoxide, which resulted in the formation of blisters on the surface and gave rise to the name ‘ blister steel’. The cemented bars were sheared, bound in the form of faggots and then forged to produce more homogeneous bars of ‘shear steel’. Further shearing, binding and forging produced ‘double shear steel’.

Benjamin Huntsman in 1742, when searching for steels of improved homogeneity for his watch springs, discovered the crucible process. This process used a coal fire and very high temperatures were generated by a forced draught, the sealed crucibles being placed in a flue between the firegrate and chimney. Using wrought iron and blister steel as the melting stock, Huntsman was able to produce high quality high carbon steels. The molten steel was cast in ingot form and then forged by water-driven tilt hammers. The process was used on a commercial scale by 1751 for making springs and cutting tools for agricultural and domestic use.

3.3.2 The Bessemer Converter
One of the most far reaching discoveries in steelmaking was the invention of the Bessemer converter in 1855 (see the previous chapter). The oxidation of carbon, silicon and phosphorus generated sufficient heat to raise the metal temperature, thereby producing molten steel. Although Bessemer’s original vessel only held about 365 kg of metal, the process was rapidly scaled up to give 5–6 tonnes heats and by 1900 heats of as much as 20 tonnes were being produced.

The introduction of the Bessemer process was not without its problems despite the extremely rapid process rates; each heat could be converted to steel in a period of 15–20 minutes, compared with a 2 hour cycle time for 1 tonne of puddled iron. Firstly, the early Bessemer converters were lined with siliceous refractories, giving rise to the term acid Bessemer process, and could only be successful when using irons of low phosphorus and high silicon contents. But the highly siliceous slag, with its requirement for siliceous refractories, would not retain the oxidation product of phosphorus and phosphorus remained in the molten steel, thus causing embrittlement. In fact, several steel producers had introduced the Bessemer process only to find that, because of their phosphoric ores and consequent high phosphorus pig iron, they were unable to produce satisfactory steel.

As Bessemer had consistently been looking for a new method of producing
wrought iron, his early attempts to cast the steel in the form of an ingot failed. Mushet demonstrated that additions of manganese acted as a deoxidant and also removed the harmful effects of sulphur. The use of manganese additions at the end of the blow in the Bessemer process thus produced a metal that truly could be called steel, and that could be cast in ingot form. Other equipment developments included the use of trunnions to allow the vessel to be tilted for charging and pouring. A major development was the change in refractories to a basic lining, thus allowing a basic slag to be used that was capable of removing phosphorus from the iron during the blow. The process was developed by Thomas and Gilchrist and was publicly demonstrated in 1879. This widened the scope of the Bessemer process in that the basic Bessemer converter could now be used to make steel from high phosphorus iron. The basic Bessemer converter was lined with rammed dolomite (magnesia bearing lime) mixed with tar. The lining was then heated to burn the tar, leaving a residue of carbon which bonded the dolomite particles. By 1900, the relative use of acid and basic Bessemer converters was dependent on the types of ore available. In the USA, 77% of converters were basic, whilst in the UK only 13% were.

The early production of Bessemer steel involved melting solid pig iron in a cupola type furnace. The cost of manual pig breaking and the re-melting process were eliminated by the use of ‘direct’ or ‘hot’ metal, i.e. carrying molten iron from the blast furnace and charging it, still molten, into the converter. Cast to cast variations in quality were avoided by using a ‘mixer’ furnace of some 200–300 tonnes capacity which greatly reduced the variability. The direct metal practice had been introduced by the turn of the century and the increased production rates were accompanied by corresponding changes in casting pit practice, including the introduction of casting cars which allowed the necessary rapid movement of filled moulds away from the casting bay and empty moulds into the bay.

3.3.3 The Open Hearth Furnace
Shortly after the development of Bessemer steelmaking in 1855, a second steelmaking process was invented by Sir William Siemens in 1867 by merging the regenerative heating principle with Martin’s patented process of diluting pig iron with wrought iron scrap prior to refining. The process became known as the Siemens–Martin open hearth process.

An important feature of the regenerative system (preheating the incoming air in one of a pair of checkerwork chambers whilst heating the other chamber by the passage of waste gases) was that much higher temperatures could be attained. A reverberatory furnace, with preheated air, could generate temperatures well above 1600°C and could therefore melt any steels. An important aspect of the open hearth process was the extensive use of scrap steel and wrought iron. Scrap at this time was abundant and cheap, thus giving a competitive edge to the open hearth process; the Bessemer process was not able to use scrap in any significant quantity at this time. Siemens’ early furnaces had capacities of the order of 5–6 tonnes. However, by 1867, the open hearth furnaces were fuelled by preheated producer
gas (Siemens having invented the gas producer in 1861). Both the producer gas and the air were preheated in the regenerative system by having separate chambers for the gas and air.

As was the case for Bessemer steelmaking, the refractories were of siliceous brick and sand (gannister) and the process was known as the acid open hearth process. In the same year, as was the case for the Bessemer process, Thomas and Gilchrist's basic process was publicly demonstrated to be effective when applied to the open hearth furnace. The hearth was constructed with a monolithic dolomite lining, although the siliceous roof was retained.

Scaling up the size of these furnaces was inevitable and by the turn of the century, the furnace capacities were of the order of 25–30 tonnes. However, even in 1900, companies in the USA already had plans for 50 tonne capacity furnaces. A summary of the production of steels by the various processes between 1870 and 1900 is shown in Fig. 2.

4. HOT ROLLING PROCESSES, CIRCA AD1900

Although a fuller discussion occurs in the previous chapter, it is worthwhile to reiterate some of the features of the state of the art in 1900, in the following sections. Ingots were used exclusively as the starting point for hot rolled products. The main object of hot working was to produce specifically shaped products but also to close up unsoundness in the ingot, to obtain dimensional accuracy, to homogenise the product and control fibreing, whilst minimising scrap arising from cropping and

![Fig. 2 Early UK steel production, 1870–1900.](image-url)
edge shearing. Starting with the work of Cort in 1783, the development of three-high mills in 1857 and of reversing mills after 1866, many improvements had been made with the use of backing rolls, universal mills for slabbing and edging and aids to mechanical handling. Output greatly increased.

The ingots in general use were 3–5 tonnes weight and much of the rolling, particularly of billet, bar and rod, was by manual manipulation, aided by levers. For larger work, power levers and lifting tables were used with various mechanical manipulators to turn material. The ingots were heated in gas or coal fired soaking pits and the need for temperature control to prevent burning was understood, although burning was not fully differentiated from over-heating.

Cogging and plate mill rolls operated at 30/60 rpm, i.e. < 18 m min⁻¹, bar and billet mills at 110/200 rpm (≈ 90 m min⁻¹) and wire rod mills at 500/600 rpm (≈ 220 m min⁻¹). As the maximum rolling speed for manual manipulation was ≈ 180 m min⁻¹, the smaller diameter wire rod mills often used mechanical guiding into the roll passes and the rod was then coiled, using a mechanical coiler and an independent drive. The ever increasing demand for wire products can be seen from the fact that in the USA alone, output of wire rod was 850,000 tonnes in 1900 but by 1909 it had risen to 2,350,000 tonnes, almost 10% of USA steel production.

Whilst it was known that lower finishing temperatures gave better ductility and toughness, no real attempt was made to control finishing temperatures. Many types of section were rolled, from angles through H and I beams to rail sections. The problem of cooling of the thinner parts of complex sections was appreciated, with its effects on distortion and straightness. Shears and hot and cold sawing were available for blooms and billets. There was considerable knowledge of the deformation behaviour of hot steel in the rolling pass, with a good, though empirical, appreciation of draught design. The main mill drives used steam power and sometimes gas fired boilers, or even the slightly more efficient gas engines, using blast furnace or coke oven gas. Electric motor drives for bloom, slab or plate rolling were not introduced until 1915 in the USA. The reversing mill engines were masterpieces of precision engineering in terms of smoothness of operation, acceleration and control of mill speed. The smoothness and speed of the reversing operation was remarkable. The heavy demands for railway materials, and tyres in particular, had led to the development of ring rolling. The ingots were often multi-facetted, heavily top cropped and cut into cheeses which were then upset, the centre punched out and taken to the ring rolling mill.

4.1 Billet, Bar and Section Rolling

Billet mills require little attention, with billets up to 15 cm square being produced in large quantities without reheating. Equally a variety of sections were produced and straightening was carried out manually or in a press, and occasionally an early form of roller straightening was effectively used for lighter sections. Small round bars were produced on mills often with reversing capabilities, and such mills also produced small square, T and angle sections. Much rivet steel was rolled.
in this way, rivetting being the only means of joining in constructional engineering.

4.2 Flat Product Rolling

Plate mills employed reversing with rolls up to 1 m diameter and 3–4 m wide. Ingots were slabbed, edged, reheated and rolled to boiler or ship plate. Plates up to 30 mm thick could be produced. Armour plate mills were of course much heavier, employing larger rolls, but in principle were just large plate mills with high power engines. In general, the lengths and widths of plate were constrained by transportation capabilities. Hot sheet, 15 mm thick or less, was produced in two-high mills with manual handling. The lengths of sheet were limited.

Strip mills produced 3 mm thick by some 250 mm wide strip, starting from flat bars. Good surface finish was the aim and to help achieve this rolling was at a much lower speed. Straightness was a problem. Coiling was in its infancy and light strip was even folded into skeins (like wool). For welding into gas pipes, fairly long lengths were manufactured.

4.3 Rod Rolling

Rod mills of many types were in operation, often specific to a particular works, in a three-high configuration and used billets as a starting point. They were often manually operated at the slower speeds but the more modern mills used guides and repeaters. The rolled rod looped out between passes and as the loops became larger during rolling the loops were spread out over the rolling mill floor. For making long lengths of rod, 'continuous' mills were used with mechanical reeling, and the rapid deformation produced heat so that the cooling as the rod became thinner was offset. In the 30 years up to 1900, rod mills increased their output speed more than twenty fold.

5. FORGING, CIRCA AD1900

Steam hammers were mainly used, but difficulty in penetration of the work was encountered, particularly in the larger forgings. Large ingots were difficult to produce owing to segregation and the limitations of the hot topping techniques available. The ingots were often multi-faceted. There was little clear understanding of the mechanism of solidification, especially in the larger ingots, so that fluid centres were not an unusual problem. However, it was observed empirically that the ingot lengths should not be less than 1½ times the diameter and a length/diameter ratio of 3 or 4 was common. The ingots were mounted on porter bars operated by teams of men with geared chain driven rotation of the workpiece under the hammer. There was little or no control over the temperature as forging progressed, and this situation did not alter for very many years. Press forging was started by Bessemer's
experiments in 1856–1863 using hydraulic pressure, and by 1900 many makes and designs of press were in use, employing continuous or intermittent action; quick action presses had been developed. It was appreciated that presses gave superior penetration of deformation compared with hammers, and worked metal more thoroughly and uniformly with more accurate dimensions. Surface pressures of 45–80 MPa were general for mild steel, but twice this pressure was required to fill a recessed die accurately, which of course was also achieved through hammer forging, using open or closed dies. Hollow shafts and drums could be forged either by hammer or press.

6. TUBE- AND PIPE-MAKING, CIRCA AD1900

Tube- and pipe-making in 1900 already had a fairly long history, the first pipes for gas lighting being made about 1815 using discarded musket barrels screwed together. By 1900 tube-making methods could be categorised as rivetting of steel plates for very large drums, as weldless tubes made by hot working a solid billet, or as forming a rolled strip into a tube and welding the edges by a forge-welding process.

Weldless tubes were made from billets. A hole was drilled through the billet axis and the billet heated, inserted into a press and a ram was driven down through the billet to expand the hole in several passes. The pierced billet was then rolled in a rolling mill with a mandril positioned in the pierced hole, over which the tube was rolled. Various modifications to the process were used, especially for small tubes. For longer tubes, the rolled tube was drawn cold on a drawing bench, again using a mandril and a conical die. Prior to such drawing, the tube was annealed, pickled, dried and oiled. This annealing was carried out between every pass, so the method was laborious and time consuming. Such tubes were used in the boilers of large ships and were up to 120 mm diameter with wall thicknesses of 8 mm, whilst ordinary boiler tubes were some 80 mm diameter. Bicycle tubing was produced in diameters of 40 mm in lengths of as much as 6 m. Weldless tubes, for example for storage cylinders were also produced from flat circular plates by a deep drawing process, again with inter-pass annealing. Special processes were also employed, for example the Mannesman process, patented in 1885, which produced a central cavity in a billet by cavitation resulting from the tendency for a billet to 'work hollow' when subjected to the action of specially shaped rolls. The process, known as pilgering, then allowed the cavity to be perfected by rounding and smoothing with the use of a mandril.

To make welded tubes, hot rolled strip of appropriate dimensions was heated and passed through a specially shaped die on a draw bench, which bent the strip into a tube configuration, whilst planing the abutting surfaces which were in effect forge welded together. After the welding process the tubes could then be drawn hot or even cold drawn which improved the surface condition and imparted stiffness. Various welding configurations such as lap and butt pressure welding were used.
7. COLD WORKING PROCESSES, CIRCA AD1900

The two main cold working processes in 1900 were wire drawing and cold rolling bar, sheet and strip.

7.1 Wire Drawing

Wire production has a history going back into antiquity, gold wire of flat section and possibly made by hammering was used for jewellery in Egypt as long ago as 2750 BC and by Assyrians and Babylonians as far back as 1700 BC. How, when and of what material round wire was made is not known. The draw plates were apparently of iron pierced by holes. Chain armour in the Crusades was probably made from drawn wire and records of iron wire production in Europe go back to AD1250–1500. The unprecedented increase in the demand for wire, particularly steel wire, in the second half of the nineteenth century was owing to its use as agricultural fencing, for telegraph wire, all forms of wire rope, smaller nails and fasteners, baling, springs and many domestic applications from pins and needles to garment stiffeners. This led to major developments in the wire drawing industries in terms of dies, lubrication, coatings, continuous drawing processes and even heat treatment.

In 1900, whilst wire was still produced by drawing through individual dies with coiling on a drum between dies, the most modern mills used continuous drawing through several dies in line with a power driven barrel on which a few loops of wire were wound between the dies. How many dies were in line depended on the reductions given in each die and the need to anneal. The speed of drawing could be as high as 220 m min⁻¹ and exceptionally for the finer gauges up to 300 m min⁻¹. There was difficulty in drawing the very finest wires owing to steel cleanness. The dies were often of hard white cast iron for larger diameter wires, but smaller diameter wires were drawn through hardened high carbon steel dies. For the very finest wires, diamond or ruby dies could be used. Lubrication was by oil or tallow for the larger sizes (dry drawing) and by soap solution or other liquid lubricants (wet drawing) for finer wires. Galvanising of wire was well established for corrosion protection, especially for agricultural purposes.

The preparation of the wire rod for cold drawing to wire was not too dissimilar from today, comprising pickling to remove scale, washing in lime water and drying. Interestingly, it was known that too severe pickling could cause many breaks during drawing, and it was believed this was a result of H₂ pick-up; in fact it was one of the earliest known cases of hydrogen embrittlement. The reductions used varied depending on the starting and finishing sizes, the number of passes and their reductions, together with the ability to apply the required pull and the properties required. No mention has been found of back-pull being used. Annealing was carried out at appropriate stages, the annealing being carried out in sealed pots at temperatures above the Ac₃ and slowly cooling. Apparently no sub-critical annealing was used. After every annealing treatment the wire required to
be pickled again, washed and dried, so that quite a loss of material could occur. Patenting had not yet been invented, as there was no knowledge of the isothermal transformation of austenite to pearlite, but a product called ‘patented’ steel was produced in which the steel wire was passed through a heated muffle furnace into an oil bath to harden the wire, and then into a lead bath to temper the hardened product. It is unlikely that the oil cooling produced martensite, and indeed may well have produced fine ferrite/pearlite in the plain carbon steels used. It was not uncommon for drawn wires to have tensile strengths in the range 600–1800 MPa, and the ‘patented’ special wire could be of 2300/2600 MPa tensile strength. Piano (high C) wire of 0.7 mm diameter had been produced with a tensile strength over 3200 MPa; this was considered unique.

7.2 Cold Rolling

Cold rolling processes were not widely used, two-high mills produced limited lengths of cold rolled strip. Occasionally where extreme dimensional accuracy was required, bars were pickled to descale them and then cold rolled between finely finished white cast iron grooved rolls. There was no demand for wide cold rolled sheets of great lengths, the main product being strip of some 150 mm wide, which was then slit into thinner widths to make a variety of products such as pen nibs, umbrella frames, etc. Such material was made by pickling hot rolled strip, close annealing in boxes and rolling in oil between very short stiff rolls which could be polished by rolling empty. Tin plate was, however, made from cold rolled sheet. The actual tinning process will not be described, but tinplate was used for canning food and for baths, milk cans and pails etc.

8. HEAT TREATMENT, CIRCA AD1900

In 1900 most of the standard heat treatment processes had been developed, although the precise mechanisms of what was occurring were still open to debate. Heat treatment furnaces were predominantly gas fired, often with a muffle cavity. Annealing was well known and both full annealing using high temperatures and slow cooling, and lower temperature annealing, sometimes called process annealing, was also practised, but the fact that this was most probably sub-critical annealing was less well appreciated, because the first tentative Fe–C equilibrium diagrams had only been postulated in 1896/1897. Annealing of cold worked materials, i.e. sheet and wire, was carried out in sealed pots or boxes to prevent excessive oxidation. Normalising, i.e. air cooling from high temperatures was also practised.

Quenching was known to harden steels, although it was believed that plain carbon steels, except of high carbon content, did not harden greatly. However, certain alloy steels containing W, Cr and Mn were known to possess the ability to
harden on air cooling. Equally the effect of tempering in relieving some of the hard-
ness and introducing a measure of ductility was appreciated.

In the field of cast iron, the malleabilising treatments were of long standing and
were carried out in closed boxes employing either reducing conditions (black heart)
or oxidising conditions (white heart). Also some surface hardening was carried out
on steels using case carburisation in boxes packed with a carburising agent.
Application of flame surface hardening was available, but the control was minimal.
It should be emphasised that the understanding of all these heat treatment pro-
cesses was in its infancy.

9. INVESTIGATIONAL TECHNIQUES, CIRCA AD1900

The main laboratory facility was chemical analysis and the chemical laboratory had
pride of place in the steelworks. Chemical analysis was almost exclusively by wet
methods, which were often slow and laborious, and this limited the speed of feed-
back to the control of steelmaking processes, which consequently were slow.
However, spectroscopy had been used and gravimetric and colourimetric methods
were employed.

The mechanical testing laboratory, or testhouse, was also an integral laboratory
facility. Hardness tests included the Brinnel, Shore Scleroscope and scratch testing
methods, together with a penetration test. Tensile and impact testing was also
carried out, usually at room temperature and limited fatigue testing was available.
In 1900, creep testing was not available.

With regard to physical testing, thermal analysis was in use together with mag-
netic analysis and electrical resistance studies, and some dilatometry (specific
volume) studies to follow the allotropic transformations. The beginning of an
appreciation of the Fe-C equilibrium diagram had commenced in 1896/1897
(Roberts-Austen) with a fairly realistic diagram being published by Roozeboom in
1900. Already there was some understanding of the difference between the
metastable Fe-cementite and Fe-graphite (stable) diagrams. X-rays had only been
discovered some 5 years earlier (1895) and their use for X-ray diffraction and crys-
tal structure determination was some 15 years in the future.

Optical metallography, introduced by the work of Sorby (1863), was well devel-
oped and the standard of preparation and photomicroscopy was surprisingly
high in the best practice. But the interpretation of the mechanisms by which vari-
ous structures formed was yet in its infancy, considerable dispute occurring on
the place of troostite and sorbite in the microstructural hierarchy. Many investi-
gations were being made into the etching of steel for microscopical examination
and for revealing segregation and the ubiquitous fibre effects which it was
appreciated was a result of deformation of segregated regions. In general, there
was the start of understanding of solidification processes, although discussion still
occurred on the crystalline nature of steel. The effect of temperature on grain size
and grain growth was being investigated, but quantitative measurements seem
not to have been made, although it was known that coarse grains weaken and embrittle.

Much work had been done on the metallography of deformation and of slip lines, slip bands, Luders bands, mechanical twinning (Neumann bands) and deformation paths in different structures. Intergranular and transgranular deformation was distinguished and the deformation markings during fatigue were established at least as early as 1903. The fact that slip planes were crystallographic was known, but an understanding of the precise cause of work hardening was many years in the future.

Rupture and fracture studies were quite well developed. There was recognition of the distinction between intergranular and transcrysalline fracture as early as 1896 and the intergranular nature of fracture in burnt steel was known. The extensive work of Brinell on fractures of different types in steels with different microstructures was still some years in the future. Surprisingly, the role of inclusions or other second phase particles on ductile fracture was barely appreciated. One can almost infer from a rather confused literature that the possibility of inclusion interface decohesion was being hinted at and cusps in the fracture were illustrated but little understood. Also, there are hints well before 1900 that the phenomenon of the ductile-brittle transition had been observed. The identification of non-metallic inclusions was in its infancy, especially in the case of various types of oxides, although the difference between forms of sulphide was well established.

10. CONCEPTS, CIRCA AD1900

In 1900, ferrous metallurgy was only beginning to develop into a science from an art largely practised by experienced craftsmen of no extensive scientific training. As conceptual developments are largely the consequence of scientific understanding, it is perhaps to be expected that the concepts were rudimentary. Nevertheless, certain conceptual appreciations were in their infancy, although their development was retarded owing to the lack of investigational techniques for the high resolution study of microstructure and for the accurate chemical analysis of a wide range of the elements present in the composition of steels.

There was, in 1900, the first published Fe-C equilibrium diagram clearly of the form known today. Following the seminal work of Gibbs in the later part of the nineteenth century and his deduction of the phase rule in 1876, there was increased interest in not only the determination of more accurate equilibrium diagrams but also the application of the phase rule to try to ensure they complied with thermodynamic principles. Even so, some highly unusual diagrams were often produced. But most significant, conceptually, was the idea of the allotropy of iron, although X-ray determinations of crystal structure were still in the future, and this even led to misconceptions such as the debate as to the nature of $\beta$ iron (non-magnetic $\alpha$) and its relationship with martensite and hardening. However, the idea of allotropy led on to the concept of transformations in steels and the effects of heating and cooling. The nature of martensite was
attracting much speculation, the true nature again being obscured by the lack of the necessary investigational techniques, although Le Chatelier came near to the truth.

In the field of thermodynamics, the use of elementary data on heats of formation of various oxides had been applied to the reactions in the blast furnace to compute heat and mass balances and work towards optimum burden compositions. Also thermodynamics had been applied to the order of oxidation of the elements during steelmaking, and the law of mass action had been applied.

Whilst the mechanisms of work hardening were unknown, there was considerable speculation about the mechanisms of slip, which was known to be on crystal planes, but precisely what caused hardening excited much discussion. This was developed by Beilby in 1904 using an amorphous layer theory which paved the way for much further work. Equally, the general concepts of fracture were being developed and the observations that had been made were being extended and interpreted when improved techniques for fracture examination became available. The slow and painstaking development of concepts was clear, despite the often detailed experimental observations, and it is probably that this was owing to the lack of knowledge of crystal structure, the nature of grain boundaries and especially the limited resolution of optical metallography.

11. ALLOY STEELS, CIRCA AD1900

In 1900, only 100,000 tonnes of alloy steel were made, which accounted for about 0.35% of total steel output. Consequently alloy steels were in their infancy and a large proportion of them were used as tool steels. Most steels were plain carbon, ranging from very low carbon steels to hypereutectoid steels, which were often crucible steel. Most of the plain carbon steels were made by Bessemer or open hearth processes and a wide variety of sub-classifications was used. Most steels were plain carbon, ranging from very low carbon steels to hypereutectoid steels, which were often crucible steel. Most of the plain carbon steels were made by Bessemer or open hearth processes and a wide variety of sub-classifications was used. Often the steel contained a normal manganese content of ~ 0.3-0.5%, but steels could be produced up to 1.5% Mn or even higher. The use of Mn to prevent the hot shortness owing to O and S was well known. But the Mn addition, spiegeleisen, was usually high in carbon, as was silicon spiegel which was used as a silicon addition, so that the steels had high C contents. The low carbon versions of spiegel necessary for the lower carbon-manganese steel (as produced by Mushet) were expensive.

The birth of alloy steels is often credited to Faraday and Stoddart in 1818/1820 but this probably over exaggerates their importance. In fact they made up alloys containing 1-2% of a wide range of individual additions, the analyses not being recorded but determined by Hadfield in 1931 when the specimens were discovered at the Science Museum. Some of the additions were rather exotic. There was no demand at the time for better steels, so in effect Faraday and Stoddart were examining metallurgical curiosities and with the highly impure base it is doubtful if commercial exploitation would have been possible. Elements such as Cr and Ni were at that time difficult to obtain.

The first industrial exploitation of an alloy steel was by Mushet in 1868, who
took out many patents for Ti (1859), W (1859) and Cr (1861) additions. He also probably made a contribution to manganese alloy steels. The crowning achievement of Mushet was the development of W steels, and the realisation that these were air-hardening with no risk of quench cracking. Cr steels were probably first manufactured in the USA (1871) and France (1878) and all were high C, low Cr. Mushet's tungsten steel was exploited as a tool material, in fact the forerunner of the high speed steels. By 1900, the Bethlehem Works in the USA were producing a 1.8%C, 8%W, 4%Cr steel and five years later, according to Hadfield, almost a typical 18-4-1, W-Cr-V high speed steel.

There now comes the seminal researches of Hadfield in 1882-89 which led to the development of the 12%Mn austenitic steels and the successful 4%Si transformer steel, first used in an experimental transformer in 1903. It is interesting that the 12%Mn austenitic steel was developed because of the high carbon ferro-manganese used, and if low carbon ferro-manganese had been used a very different and transformable steel would have resulted. As Keown states 'fortune again shone on Hadfield's choice of ferro alloys', a low carbon ferro-silicon being used for the 4%Si transformer steel. Hadfield was interested in silicon for tool materials. It is possibly a tribute to his perspicacity that high Si contents are used today in ultra-high strength steels.

Possibly the first and most important development in steels for constructional purposes was the addition of Ni to carbon steels and these steels were first described by Riley in 1889, although they had previously been made in France and possibly elsewhere. A more complete description of Ni steels was given by Colby in 1903. The ability of Ni to impart ductility (and toughness?) at very low temperatures had been established by Hadfield by 1905.

The position with respect to chromium additions is interesting, but it is not possible to go into the long and involved history of the use of Cr which eventually led to the development of the first commercially viable stainless steels by 1915. Many claims and counter claims for priority have been advanced, often on a nationalistic basis. Suffice it to say that Faraday noted the corrosion resistance of chromium steel (or iron) in 1820 and Berthier confirmed this in 1821. But the imparting of corrosion resistance by Cr was not universally accepted for many years owing to the use of inappropriate corrosive media, i.e. sulphuric acid, and the lack of appreciation of the role of carbon in lowering the effective Cr content dissolved in the steel. In fact Hadfield had concluded that Cr did not impart corrosion resistance in 1892, having used strong H₂SO₄ as the corrosive medium. By 1900 however, the detrimental effect of carbon had largely been recognised (Carnot and Gautal, 1898) and by 1911 Monnartz had conclusively demonstrated the corrosion resistance of Cr steels. Hadfield (1898) and other workers had appreciated the 'hardening' effect of Cr additions to carbon steels and possibly the Americans (Bauer, 1865) were the first to produce low Cr steels, to be followed shortly by France (1886) and Germany.

Other alloy steels had also been investigated, although perfunctorily, and by 1900-1905 cobalt, copper, aluminium and titanium steels had been manufactured experimentally. Molybdenum does not yet seem to have made an appearance but
boron additions of 0.5% had been tried, the alloys not surprisingly being brittle. The hot shortness produced by copper had been recognised by Percy as long ago as 1864 and there was universal agreement of the detrimental effects of S and P. Because most of the developments which were being attempted were of an empirical nature, the variable degree of purity with respect to such detrimental elements as S and P, not surprisingly, could lead to conflicting results and some confusion.

It can be seen that by 1900 there was a very great interest in, and active work on, the effects of alloying elements in steel. This can be seen from the many reports of the Alloys Research Committee published by the Institution of Mechanical Engineers in the decades either side of 1900. Such reports were contributed to by workers from many countries and their publication stimulated much research in the USA, Germany, France, Japan and Sweden, as well as Britain. The stimulation given to research by this empirical early work cannot be underestimated, and particular mention must be made of the extensive and systematic studies of the role of alloying elements on the allotropy as typified by the work of Osmond and other workers in 1895–1915. In fact the eminent metallurgists who worked in this period are too many to be recognised individually. Tribute must also be paid to the metallurgists, often with a background in the physical sciences, whose intuitive appreciation of the mechanisms involved was quite remarkable. In this respect, there was no more eminent worker than Le Chatelier whose contributions were quite outstanding.

12. DEVELOPMENTS IN IRONMAKING AND STEELMAKING IN THE TWENTIETH CENTURY

12.1 Developments in Ironmaking in the Twentieth Century

The most obvious change in ironmaking is the sheer size of the furnace. The early blast furnaces at the time of the substitution of coke for charcoal were about 7 m high, having a hearth diameter of about 2 m. By the early twentieth century, furnace heights in the UK had reached some 26 m, with a hearth diameter of 4 m, whilst in the late twentieth century, heights of 32 m and hearth diameters over 10 m are not uncommon.

The increased volume of the furnace implies an increased ironmaking capacity. Within the twentieth century the total tonnage of pig iron produced in the UK has varied by a factor of three, but the really striking statistic is that in 1900 some 9 million tonnes of pig iron were produced from 403 blast furnaces, whereas in 1996 some 12.8 million tonnes were produced using only 9 furnaces. The output of pig iron per furnace in the UK has increased progressively from 20,000 tonnes per annum to 1.4 million tonnes. It should be pointed out that these are average figures for UK production; considerable variation still exists from furnace to furnace. The production of iron in the largest of the UK furnaces amounts to 3 million tonnes per
annum, whereas in the smaller furnaces, the production is of the order of 1 million tonnes.

Whilst part of the increase in production rate over the last 100 years can be attributed to the increased volume of the blast furnace, other technological innovations have contributed to the sixty-three fold increase in productivity that has been observed over the twentieth century. These innovations include ore preparation, high top pressure and modifications to the composition of the air blast.

12.1.1 Ore Preparation
The size ranges of materials constituting the blast furnace burden, i.e. iron ore, lime and coke, are important in providing a porous bed through which the gases produced by combustion at the tuyeres can pass easily. Excessive amounts of fine particles and dust can choke the pores between the larger lumps, and impede the passage of gases. Crushing and grading systems were already in use before 1900 but the ‘fines’ would have represented significant losses unless some method of agglomeration had been found. Various agglomeration methods have been developed such as briquetting, pelletising and sintering. Of these perhaps the most widely used is sintering.

Fine ore and coke fines (breeze) are mixed and passed under a ignition hood which serves the purpose of igniting the coke in the surface layers of the mixture. As the burning mixture passes along a moving grate, air is blown through the mix to maintain the combustion and the coke in the mixture is totally consumed (burn through). In this process, the fine ore particles are fused together to give porous blocks of sinter, with sufficient strength to prevent an undue proportion of fines when the sintered blocks are crushed to a suitable size. The porosity of the sinter makes the iron oxide more easily reduced than the compact ore and permits more rapid driving of the blast furnace. The elimination of fines also reduces losses of fine particles from the furnace top into the dust catcher.

Although originally introduced as a means of utilising ore ‘fines’ and coke breeze, the operational benefits of using sinter were soon realised and it was used in increasing proportions in the burden. Two Greenawalt sintering strands were installed at Scunthorpe in 1936 and a Dwight Lloyd pallet strand was installed a few years later. A 100% sinter practice has been used during the latter half of the twentieth century, although it is not applied universally.

The importance of the lime, silica and alumina contents of the burden in providing a low melting point slag was well appreciated in the earliest days of the blast furnace and burdens were calculated to give the desired lime/silica ratio. The building of larger furnaces and the attendant mechanisation to deal with the larger volumes of material provided an excellent opportunity for mixing ores of different basicity by the practice of ore bedding, which has the added advantage of smoothing the variations in ore composition by layering them in the ‘bed’. If the overall ore composition is too ‘acid’ (siliceous) then limestone has to be added to develop the correct lime/silica ratio. A Robbins–Messiter bedding system was introduced in
1934 at Scunthorpe. This technology has been applied to sinter and by adding limestone fines to the sinter mixture, a self-fluxing sinter can be produced.

By having porous, well sized, lumps of an effectively calcined, self-fluxing burden, the production rates have been increased dramatically and the 'coke rate' (coke used per unit of iron produced) reduced significantly. Any citations of coke rates would be meaningless at this stage because the coke rate has been influenced by other factors which have been changing simultaneously with the introduction of sinter. For example, the iron content of the ore has been increased dramatically by selecting richer ores for iron extraction. In the UK this can be illustrated by the declining use of the lean home ores and the corresponding increase in the use of rich foreign ores. The haematite iron ore deposits of the West Coast (Cumberland and Lancashire) were quite rich in iron, containing 51% metallic iron, but the Jurassic ironstones of the Lower and Middle Lias and Inferior Oolite strata of Lincolnshire and Northamptonshire contained only 28% metallic iron. The weighted average of iron ores in the UK including those of the coal measures yielded only 30% metallic iron. Some of the richer ores from Spanish Morocco and Sweden contained 62–63% metallic iron. This change in the constitution of the burden obviously requires less fuel for the heating and fluxing of the gangue materials, whilst the increased use of sinter reduces the energy required for drying and driving off carbon dioxide from the limestone. The net effect of these, and other, changes on the coke rate through the twentieth century are illustrated in Table 2. The changes in coke rates reflect the decreased burden and the increased use of sinter. The high levels of iron extracted are influenced by the practice of adding mill scale and scrap steel to the burden, a practice that existed even before the turn of the century.

It is also worth mentioning that the working out of the UK coking coals suitable for blast furnace coke production led to the use of imported coals of very low sul-

<table>
<thead>
<tr>
<th>Year</th>
<th>Pig iron production, million tonnes</th>
<th>Ore* consumed, million tonnes</th>
<th>Coke equivalent consumed, million tonnes</th>
<th>Iron/iron ore ratio</th>
<th>Coke rate (coke/iron ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900</td>
<td>8.96</td>
<td>22.10</td>
<td>12.40</td>
<td>0.41</td>
<td>1.38</td>
</tr>
<tr>
<td>1915</td>
<td>8.72</td>
<td>21.71</td>
<td>11.43</td>
<td>0.40</td>
<td>1.31</td>
</tr>
<tr>
<td>1920</td>
<td>8.03</td>
<td>19.14</td>
<td>11.40</td>
<td>0.42</td>
<td>1.42</td>
</tr>
<tr>
<td>1930</td>
<td>6.19</td>
<td>15.33</td>
<td>7.71</td>
<td>0.40</td>
<td>1.25</td>
</tr>
<tr>
<td>1941</td>
<td>6.73</td>
<td>21.35</td>
<td>9.32</td>
<td>0.32</td>
<td>1.38</td>
</tr>
<tr>
<td>1950</td>
<td>9.63</td>
<td>20.31</td>
<td>9.90</td>
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<tr>
<td>1960</td>
<td>16.02</td>
<td>28.56</td>
<td>13.39</td>
<td>0.56</td>
<td>0.84</td>
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<tr>
<td>1970</td>
<td>17.67</td>
<td>29.52</td>
<td>13.20</td>
<td>0.60</td>
<td>0.75</td>
</tr>
<tr>
<td>1991</td>
<td>12.06</td>
<td>18.28</td>
<td>6.34</td>
<td>0.66</td>
<td>0.53</td>
</tr>
<tr>
<td>1996</td>
<td>12.83</td>
<td>19.77</td>
<td>6.32</td>
<td>0.65</td>
<td>0.49</td>
</tr>
</tbody>
</table>

* Includes Sinter.
phur content. Much work was carried out on the blending of coals, and the testing of the cokes for such properties as abrasion and impact-crushing resistance in order to produce the optimum coke properties.

12.1.2 High Top Pressure and the Blast Composition

The blast furnace is a counterflow process in which ore and coke descend through the furnace, whilst the reducing gases pass up through the porous burden, heating the burden and reducing the iron oxide to metallic iron. The process is slightly more complex in that lime from the limestone, or embodied in the self-fluxing sinter, reacts with the gangue of the ore to produce the molten slag, and also some direct reduction of iron oxide by carbon can occur. Nevertheless, the passage of increasing amounts of ore (iron oxide) through the furnace to produce more iron will inevitably require more carbon monoxide (the reducing gas) to effect the reduction. Since air contains only some 21% of oxygen by volume and the outgoing blast furnace gases contain some 14% CO₂ and 27% CO, each tonne of iron produced will consume almost 3 tonnes of air, which is equivalent to about 4500 m³ of air at STP.

Obviously the increase in cross-sectional area of the blast furnace allows an increase in production rate without any increase in the gas velocity through the furnace, but increases in production rate in a furnace of any given size require an increased rate of descent of the burden and a corresponding increase in the volume of reducing gases permeating upwards through the porous burden. Merely increasing the blowing capability of the engines resulted in higher gas velocities, which in turn led to the finer materials being blown from the top of the furnace into the dust-catcher. Also the higher blast pressures required to induce this flow tended to support the burden, giving rise to an increasing incidence of hanging (when the burden sticks in the shaft of the furnace). Consequently, methods of increasing the reducing gases whilst minimising any change in gas velocity have been investigated throughout this century. These included blast humidification, oxygen enrichment of the blast and high top pressure operation.

Blast humidification involves the addition of some 3% steam to the blast. Although the decomposition of steam into oxygen and hydrogen is endothermic and lowers the flame and hearth temperatures, this may be compensated by increasing the blast pre-heat. The decomposition of the steam to produce hydrogen results in a more reducing atmosphere with a corresponding increase in production rate. Oxygen enrichment of the blast increases the flame temperature and the production of CO for a given gas velocity. This procedure could be combined with steam injection to control the flame and hearth temperatures, whilst increasing the production rate. Trials of the use of oxygen and blast humidification were conducted in the early 1950s but have not found universal application. By the early 1960s, fuel injection in conjunction with oxygen had been tried. The use of oil, powdered coal and hydrocarbon gases were all investigated; the use of fuel injection systems naturally lead to a reduction in the coke rate, the economics of the fuel injection
process being dependent on the relative prices of high quality coke and the oil, coal or gas being injected.

As early as 1929, the flow of gases through a bed of broken solids was investigated and it was found that the pressure drop through the bed decreased as the pressure was increased. Gases flowing through the bed at high pressure plainly have a higher density than gases at lower pressures and the mass of CO passing through the bed of a blast furnace can be more than doubled without increasing the gas velocity by increasing the top pressure from the usual 115,000–253,000 Pa. The increase in CO naturally allowed a more rapid passage of ore/sinter and coke, leading to greater productivity. The increase in top pressure was achieved by a pressure valve at the furnace top by the mid 1940s and a more modest top pressure of 170,000 Pa was adopted in the UK.

Thus, the improved production rates in the blast furnace have been attained by increasing the furnace size, making extensive use of sinter and modifying the blast to produce greater reducing power. These changes have necessitated changes in the ancillary equipment and refractories used in the construction of the furnace. The increased mass of air being put through the furnace is now accomplished by the use of steam turbine driven centrifugal blowers.

The amount of hot metal that is now produced has also led to developments in ladles, which are of the Kling type (roughly spherical in shape) or Torpedo type. The Kling type is popular in sizes up to 120 tonnes whilst the Torpedo ladles have capacities of over 200 tonnes. The ladles are characterised by having small apertures for filling and discharge to minimise heat losses from the metal.

12.1.3 Chemical Control of the Iron Composition

Although little has been mentioned of the chemistry of the blast furnace and the ways in which silicon, sulphur and phosphorus contents of the iron are controlled, a novel desulphurisation procedure was introduced in 1973 in which the sulphur is removed from the molten pig iron in the ladle after the furnace has been tapped. Desulphurisation of molten iron had been developed in iron foundries in the 1950s so that when the demand for extremely low sulphur steels appeared in the early 1970s desulphurisation of the iron used in steelmaking became very important. The methods involve reaction of sulphur with elements forming very stable sulphides, predominantly calcium, magnesium and sodium. The very low oxygen activity in molten pig iron provides an ideal situation for desulphurisation because of the competition which would otherwise occur between sulphur and oxygen for the above reactive metals. The earliest processes involved calcium carbide injection and magnesium–coke additions (1973), burnt lime additions (1977), magnesium–lime (1978), soda-ash injections (1978) and salt-coated magnesium granules (1979). Using low sulphur blast furnace practice together with external desulphurisation of the hot metal has resulted in sulphur contents as low as 0.005%.

Essentially, the blast furnace process is fundamentally the same today as that used in medieval times, but the scale of operations, productivity and efficiency have changed beyond recognition. An account of some of the major changes has
been given, but many other changes associated with automation, stock line monitoring and control systems have been omitted for the sake of brevity. The developments in electricity supply (within the twentieth century) have been instrumental in the developments, as has the building of large ore-carrying ships to permit the exclusive use of foreign ores in the UK.

12.2 Developments in Steelmaking in the Twentieth Century

At the start of the twentieth century, acid and basic Bessemer converters, acid and basic open hearth furnaces, crucible steelmaking and the puddling process for wrought iron manufacture had been introduced, as discussed above. The eventual demise of the puddling process and wrought iron has already been described.

A broad picture of developments in the steel industry through the twentieth century is shown in Fig. 3, which presents the annual steel production by process. In the early years of the century the acid open hearth process (AOH) predominated and accounted for two thirds of the UK steel production, the bulk of the remainder being produced by the Bessemer process. However, by 1920 production by the basic open hearth process (BOH) had overtaken that of the acid open hearth process. Increasing the use of the basic open hearth process between 1920 and 1960 and a gradual decline of acid open hearth and acid Bessemer (AB) processes, resulted in some 80% of annual production being produced by the basic open hearth. Over the first sixty years of the century, total steel production in the UK had risen from 5 million tonnes to some 25 million tonnes.

Between 1960 and 1970 overall production increased further to 29 million tonnes and this period also saw the beginning of major changes in steelmaking methods.

![Fig. 3 UK steel production in the twentieth century.](image-url)
The open hearth process was in decline and by the early 1980s was no longer used in the UK. The acid open hearth and acid Bessemer processes had both ceased production in the 1970s. The basic Bessemer process (BB), which had been used to produce some 0.5 million tonnes each year, began to increase in popularity, particularly after 1960, although the process itself was undergoing considerable modification. By 1980 the changed process was recognised as basic oxygen steelmaking (BOS); the transition is indicated by the arrow in Fig. 3. From 1980 the two remaining processes were basic oxygen steelmaking and the basic electric arc process (BEA). The electric arc furnace was introduced as a production process in 1920 but its use increased significantly after 1950, rising to about 7 million tonnes in the UK by 1980.

The dominance of these two processes was a result of the recognition that they were efficient producers of molten steel, but they were relatively inefficient insofar as refining was concerned. Their ultimate rise in popularity was dependent upon the introduction of a 'secondary steelmaking' vessel in which the refining and alloy dressing was carried out. Several secondary steelmaking processes are currently in use, and all major steelmakers in the UK use one or more forms, as will be discussed later.

The introduction of the bulk steelmaking processes capable of producing high carbon and alloy steels clearly rendered the cementation process obsolete, the last cementation furnace in the UK closing around 1950. Crucible steelmaking (not shown in Fig. 3) was still in use in the early part of the century and was used to produce low volume high quality steels for tools, knives, shears and other cutting equipment. However, the introduction of high frequency induction melting in 1922 rapidly replaced the old crucible process. In many ways the two processes are very similar, the only difference being the source of heat. In the old process coal was the fuel but in the high frequency induction furnace the induced currents in the stock cause heating and melting. As can be seen from Fig. 3, the total production by this process is relatively small, amounting to some 100,000–150,000 tonnes per year, which is used either in foundries to produce steel castings or highly alloyed steels, such as tool steels.

Quality steelmaking practices for highly alloyed steels destined for very demanding applications such as bearing steels, heat resistant alloys and ultra-high strength missile and aircraft steels, were developed in the 1960s and 1970s. These include vacuum induction melting (VIM), vacuum arc refining (VAR) and vacuum oxygen degassing (VOD). Electroslag refining (ESR), also known as electroflux refining (EFR), was developed somewhat earlier in the 1940s in the USA. These processes are necessarily expensive and their use restricted to very special high value ultra-service steels.

Finally, from Fig. 3 it can be seen that the total production that had increased so dramatically from 1900–1970 suffered a sharp decline from 28 million tonnes in 1970 to 18 million tonnes in 1990. Certainly in the years to 1960 the demand for steel exceeded supply. In fact the authors can remember that in the mid 1950s steel was rationed to customers. A very different market developed after 1960 as Japan, then...
Korea and subsequently other developing countries installed and developed their own steel industries. This left Europe in particular with an excess of capacity, resulting in extensive closure programmes, in the UK, France, Netherlands and Germany. The response from the UK and other European industries has been to improve their efficiency and ensure that their plant performance is up to the best world standards. As an example, in the 1960s and 1970s the UK nationalised steel industry employed some 252,000 workers in producing about 25 million tonnes of steel. In the 1990s, although production had reduced to 18 million tonnes, the workforce had been reduced to about 40,000. This was achieved at least in part by increased automation and increased scale of operation. These figures go some way to explain why our metallurgist from the year 1900 would be surprised by the relative absence of workers on the shop floor, which is important in establishing an efficient steel industry. However, in the internationally competitive steel industries of the world, being efficient and working to world class standards does not guarantee success; other factors such as the foreign currency exchange rate can work adversely in countries with a strong currency, as is the case in the UK at the end of the twentieth century.

Other contributions to the increased efficiency of the industry arose from technical developments to improve the processes. Despite stiffening demands for increased steel quality, technical and scientific developments were made to improve both steel quality and manufacturing efficiency. These developments are described below.

12.2.1 The Open Hearth Process
The acid and basic processes were already in use at the start of the century. In the UK and many other countries the ability to remove phosphorus rapidly in the basic furnace led to its dominance by 1920. The process involved either a 40–100% hot metal charge from the blast furnace (or mixer furnace) or 30–40% cold pig iron, the balance being steel scrap. Cold scrap was charged into the furnace and heated with a mildly oxidising flame. Iron oxide formed on the surface of the scrap reacted with the carbon in the hot metal or molten pig iron and millscale could be added to boost the oxygen available for oxidation of the carbon (and phosphorus and silicon). Carbon monoxide was evolved from the molten metal to give the desired ‘boil’, the other oxidised impurities being held in a limey slag formed by additions of lime (CaO) and fluorspar (CaF$_2$).

Open hearth steelmaking was a relatively slow process. After melting, the molten steel was covered by a layer of molten slag, which provided an insulation layer between the metal and the flame. The problem of increasing the bath and the slag temperature arose from the use of a silica roof in both acid and basic furnaces. Silica bricks were relatively light but had a melting temperature of 1710°C. The highest tapping temperatures required for very low carbon steels was of the order of 1610°C, giving little margin for error. Developments in the open hearth process involved increasing the size of the furnace, tilting furnaces, oil firing, oxygen assisted combustion, the ‘all basic’ furnace and oxygen injection.
In 1900 furnace capacities were typically of the order of 30 tonnes. In 1913 the mean furnace capacity was about 40 tonnes but furnaces in excess of 100 tonnes capacity were already in existence, although few in number; these furnaces constituted about 2.5% of the total number of furnaces. In 1936 the mean furnace capacity was about 65 tonnes, the increase being achieved by an increased proportion of the larger furnaces, the largest being just over 100 tonnes capacity. By 1950 furnace capacities over 200 tonnes were being used and by the end of 1972 the largest furnaces in the UK had reached some 300–600 tonnes. Larger furnaces were in use in the USA and in 1960 about 12% of the US furnaces had capacities in the range of 300–600 tonnes. The tap-to-tap times were generally about 10–12 hours and thus the maximum rate of production that could be expected from the open hearth process was of the order of 50–60 tonnes per hour. However, in the majority of furnaces with capacities of about 200 tonnes the production rate was much lower.

The early furnaces were fixed furnaces and, although tilting furnaces of up to 230 tonnes capacity had been introduced by the late 1940s, fixed furnaces predominated. The largest furnaces (400–600 tonnes capacity) were not tilting furnaces. The tilting furnace facilitated the tapping process, but also allowed slag changes to be made during refining. A particularly heavy impurity load could give rise to slags of high silica and phosphorus contents. Attempts to restore slag basicity by adding lime and spar inevitably led to high slag volumes and an increased insulating effect. In tilting furnaces, however, an added option was to pour off the slag and create a new basic slag of low volume. As many of the reactions in the open hearth furnace are temperature dependent, it was natural that improved heating capability and control would be developed. This occurred to a large extent in the 1940s and 1950s when steam atomised oil burners were substituted for gas firing. These burners were enhanced by oxygen injected near the atomisers to give very hot flames. The limitations imposed by the silica roof were disposed of by the use of a basic roof introduced experimentally in Scunthorpe in 1948 and commercially in the USA in 1957. Initially a chrome–magnesite (45% MgO) brick was used but in the early 1960s mag–chrome (60% MgO) bricks were chosen in preference. These bricks have much higher densities than silica bricks and required modification of the roof design to carry the extra weight.

One of the advantages of the open hearth process over the Bessemer converter (bottom blown air) was the much lower nitrogen content of the finished steel. Nitrogen contents of 0.004–0.006 wt-% were typical of open hearth steels, whilst those of Bessemer steels were typically 0.015–0.018 wt-%. The extra nitrogen, whilst suitable for certain steels, e.g. rails, could have harmful effects on the toughness and strain age sensitivity of structural and formable steels. The advent of oxygen blowing in the Bessemer-derived pneumatic processes, however, resulted in nitrogen contents similar to, or even less than those of open hearth steels, in association with a much higher production rate. The threat to open hearth steelmakers was recognised in the late 1950s and oxygen injection systems had been tried by 1961. The most popular system of oxygen injection into the furnace was by means of a water-cooled lance, inserted through the basic roof, the end of the lance being held just above the metal
surface. Oxygen injection was started upon addition of the hot metal (molten pig iron) and continued throughout the refining period. The heat generated resulted in significant fuel savings and the process times were reduced by between 10 and 25%.

Despite these developments the production rate was inferior to other developing processes and the fate of the open hearth process was sealed. As shown in Fig. 3 open hearth steelmaking in the UK had disappeared by 1980.

12.2.2 The Basic Electric Arc Process
The carbon arc was discovered by Sir Humphrey Davy in 1800. Sir William Siemens constructed, operated and patented small arc furnaces in 1878, having demonstrated that an arc struck between two carbon electrodes was capable of melting assorted nuts and bolts placed immediately below the arc. The commercial production of steel by the electric arc process, however, had to await the development of a reliable supply of electricity of sufficient power and suitably robust carbon electrodes. Both direct and indirect arcs were tried but the greater heating efficiency of the direct arc (arc struck between electrode and metal bath) led to its general adoption. The first commercial batch of electric arc steel was delivered in 1900 in France. The first Heroult electric arc furnace in the USA was built in 1906, the capacity of the furnace being some 4 tonnes. By 1909, a 15 tonne arc furnace had been built and further increases in size occurred; the majority of furnaces involved in bulk steelmaking are now generally in excess of 100 tonnes capacity, although many arc furnaces of lesser capacity are used in steel foundries. A few furnaces of 400 tonnes capacity have operated in the USA although furnaces of 200 tonnes capacity are not uncommon.

The Heroult electric arc furnace is of circular plan with a bowl-like hearth. There are usually three electrodes which fit through the domed roof, disposed at the corners of an equilateral triangle. The electrodes can be lowered or raised individually in order to maintain a stable arc between the graphite electrode and the metallic charge. To facilitate rapid charging the whole of the roof and electrode assembly can be raised and swung aside. The charge, which is predominantly scrap, is dropped into the furnace from baskets, the furnace roof swings back into position and the arcs are struck to commence melting. A small proportion of pig iron is charged to promote a carbon boil. Refining is effected by slag control and the arc furnace can be tilted to get rid of the primary slag, and a new slag formed to reduce the sulphur level. The high proportion of scrap in the charge made this furnace a natural successor to the open hearth furnace, and a complementary process for the Bessemer and other pneumatic processes.

There have been many developments to increase the production rate of arc furnaces, one of the most obvious being to increase the arc power. Installed power capability in the early 1950s was of the order of 200 KW/tonne. This had increased to 600 KW/tonne by 1976 resulting in a significant reduction in meltdown time. The use of oxygen lancing had been introduced in the early 1950s and resulted in more rapid refining, but in 1978 the energy input for melting was augmented by the use of oxy-fuel burners. The increased energy input by these methods was facilitated
by the use of water-cooled walls (1974) and the water-cooled roof (1978). Although a direct current single electrode furnace has been used, which tends to avoid the repulsion effects of three arcs towards the walls of the electric arc furnace thereby increasing furnace life, this system does not appear to have been adopted extensively.

Other developments having a significant effect on tap-to-tap time were the introduction of secondary ladle refining (1970) and subsequently the ladle furnace (1982). Given that major impurity removal and attainment of a suitable teeming temperature could be downloaded to a ladle, the turn round time in the electric arc furnace is clearly reduced. Scrap pre-heating was also adopted in 1984 in order to reduce further the melt down time. Such measures combined with mechanical innovations such as the eccentric bottom taphole, which permits slag-free tapping, have resulted in tap-to-tap times of the order of 70 minutes. The production rate of the electric arc furnace is thus increased to above 100 tonnes per hour and the attendant changes in secondary steelmaking have left the arc furnace essentially as a melting unit, for which it is extremely efficient. Secondary steelmaking will be discussed in a later section.

The feedstock for the electric furnace has also received considerable attention. The use of scrap from automobiles, low alloy steels, white goods etc., together with contamination by non-ferrous occlusions, has led to increases in the residual content of electric arc steels, particularly with respect to copper, nickel and tin, which are not oxidised in the steelmaking process. Low residual scrap has limited availability and can be expensive. There has been a substantial growth in scrap preparation, notably by either cryogenic fragmentation or ambient temperature shredding, which allows magnetic separation of the ferrous and non-ferrous components. The use of cold pig iron in the charge alleviates the ‘residuals’ problem, but the proportion of pig iron that can be used in the electric arc furnace is limited.

Considerable growth has occurred since the early 1970s in the use of direct reduced iron (DRI). This is produced by reduction of pelletised iron ore by gas, oil or coal in a vertical shaft or horizontal rotating kiln, and does not involve melting as in the blast furnace. The DRI has a controlled carbon content and low residuals and provides an additional source of iron units for the arc furnace.

12.2.3 High Frequency Induction Process

The low frequency induction furnace was first patented by Ferranti in Italy in 1877 and was used sporadically for steelmaking. The coreless high frequency furnace was developed by Northrop of the Ajax Electrothermic Corporation in the USA. The first use of this type of furnace was the regular production of commercial steels in Sheffield, UK, in 1927. Like the crucible process developed by Huntsman, the induction furnace is a melting unit and the composition of the steel produced is predominantly the same as that of the stock charged.

The HF induction process is cleaner and more controlled than the crucible
process and gradually replaced crucible steelmaking over the period 1927 to about 1950. The process is not used for bulk steel manufacture but is confined largely to foundries where capacities of up to 5 tonnes are tailored to suit the castings being produced.

The compact nature of the furnace with its built-in induction coil lent itself to special vacuum steelmaking and there are many vacuum induction furnaces in use today for the production of high quality steels.

12.2.4 Bessemer and Other Pneumatic Processes

If we accept the Bessemer process as that in which air is bottom-blown into a converter containing molten pig iron, then the early decline of the Bessemer process in the first half of the twentieth century was followed by its total demise by 1960 in the UK and other technologically advanced countries. However, there were changes made to the process which led to the development of the currently most widely used steelmaking process. Bessemer himself wanted to blow oxygen into his vessel but was severely disadvantaged by the absence of any bulk oxygen supply, but his patent included the use of air, or oxygen, or mixtures thereof.

Early experiments with air blown onto the surface of steel through tuyeres in the side of a small converter (up to 2 tonnes) led to the development of the Tropenas converter which is used extensively in foundries. The temperature in the vessel is higher than that obtained with bottom-blowing owing to the complete combustion of CO to form CO₂. Subsequently, the converter was developed using oil and air, again side-blown, for a solid scrap/pig iron charge, again on a small scale suited to foundry operations.

Developments at the Linz and Donowitz works in Austria over the period 1947–1949 led to the development of the L-D converter and commercial heats were manufactured in 1952–1953. The process involved an oxygen lance blowing vertically down onto the surface of the hot metal and was successful provided that the iron was low in phosphorus. In the late 1950s, the process was further developed by using the oxygen as a carrier gas for powdered lime, the lime being injected into the metal, producing a basic slag, and allowing dephosphorisation, and therefore the processing of high phosphorus iron. This process was known initially as the LD–AC process but formed the core of the processes now known as basic oxygen steelmaking (BOS) or the basic oxygen process (BOP).

In Sweden, in 1952–1953, Kalling developed a process (KALDO) which involved top-blowing with oxygen, but the cylindrical vessel was rotated at some 40 rpm when the axis of the vessel was 20° from horizontal. The idea was to expose metal to the oxygen jet but the process was mechanically demanding and is now obsolete. A similar process carried out in a horizontal cylinder rotating at about 3 rpm and known as the Rotor process has similarly become obsolete.

Early attempts to inject pure oxygen in bottom-blown converters showed high wear in the tuyere areas owing to the much higher temperatures generated. The problem was overcome by mixing the oxygen with either carbon dioxide or steam, thereby taking advantage of the endothermic reactions in the decomposition of the
diluents in the vicinity of the tuyeres. A very low nitrogen (VLN) process was
developed at the Port Talbot Works of British Steel which operated through the late
1950s and 1960s. The very low nitrogen title refers to the low nitrogen content of
the steel produced using the oxygen/steam blowing process. In 1967 Brotzman of
the Eisenwerke Gesellschaft Maximilianshutte in Germany, working in collabora-
tion with L’Air Liquide Montreal of Canada, developed a system where the
oxygen jets in the converter bottom each have an annular flow of hydrocarbon gas.
This process, designated the OBM process, was licensed to the United States Steel
Corporation at their Fairfield and Gary Works in 1974. The process was operated
with 200 tonne capacity converters and became known as Q-BOP steelmaking. In
1971 Creusot-Loire and Wendel Sidelor in collaboration with plant builder Sprunk,
developed the LWS process where the oxygen inlets had annular fuel oil shields. In
this process the endothermic reaction results from vapourising and cracking the
fuel oil near the tuyere positions.

The modern BOS process uses top-blowing of oxygen to take advantage of the
additional heat, with an increased scrap proportion in the charge, up to 30%, giving
an economic advantage. The stirring action of bottom-blown processes, such as
OBM and LWS, improves equilibrium between metal and slag. In the early 1980s
basal stirring elements were introduced into the BOS process, the stirring being
effected by inert gas purging. Oxy-fuel pre-heating of the scrap prior to charging
into top-blown vessels or in situ in bottom-blown vessels, may also be incorporated.
This aspect of the process is more important when low silicon iron is used to reduce
the slag volume, thus reducing both the heat required for fusing the slag and the
lime and spar used to maintain the slag basicity.

It is clear that 1950–1975 was an extremely active period for high volume steel
process development, in which methods were found for introducing oxygen rather
than air into the converter process, as was originally suggested by Bessemer in
1855. The development of these processes was entirely dependent upon the suc-
cessful development of tonnage oxygen production by distillation of air that
occurred in the late 1940s and early 1950s.

12.2.5 Secondary or Ladle Steelmaking
Since 1970 many different secondary steelmaking systems have been introduced
involving treatments in the teeming ladle. The simplest form of ladle treatment is
that of ladle stirring and composition adjustment. Stirring is carried out by gas
bubbling either through a porous plug in the bottom of the ladle, or from a deeply
inserted refractory-sheathed lance. Argon gas is most commonly used as it is inert
and the flow of gas bubbles gives both temperature homogenisation and
homogenisation of composition following the trimming additions of alloying
elements. The ladle may have a simple lid or a snorkel may be introduced through
the liquid steel surface to hold back the slag (CAS process). In both cases the
accumulation of inert gas prevents reoxidation of the molten liquid exposed by the
bubbling procedure. The trimming additions can be made via a chute through the
top of the snorkel into the exposed metal.
Injection systems are now commonly used following their introduction for desulphurising. In 1970 demands for steels of improved toughness led to drastic changes in both sulphidic and oxidic inclusions. Although early developments were aimed at inclusion shape control, as will be discussed later, the solution to problems of ductile tearing of linepipes and lamellar tearing in offshore structures was found by reducing drastically the sulphide and oxide levels in the steel. Calcium treatment involving the deep injection of calcium silicide into the ladle proved very effective. Alternative approaches have involved lime injection or synthetic slag injection, both of which can produce similar levels of desulphurisation. Given that adequate desulphurisation of the molten iron has been achieved and sources of sulphur have been minimised in the steelmaking process, sulphur levels below 0.001 wt-% are not uncommon. The calcium silicide treatment is known to give inclusion shape control but at these very low sulphur levels achieved the inclusion is unlikely to be other than shape controlled, as the total sulphide content will be dissolved at hot rolling temperatures, thereby precluding any elongation of sulphide particles during hot working. An alternative addition method tried in the 1970s was wire feeding using a cored wire containing calcium silicide or aluminium. By putting easily oxidised additives in the centre (or core) of a mild steel wire, the additives can be introduced well below the liquid steel surface, thereby avoiding serious oxidation losses.

Aluminium deoxidised steels can be difficult to pour owing to blocking of the teeming nozzle by skeletal dendrites of alumina, the deoxidation product. In the early 1980s suitable additions of calcium resulted in modification of the deoxidation product to give a liquid calcium aluminate inclusion which does not block the teeming nozzle.

These developments provide the means to eliminate sulphide inclusions and to control the shape and constitution of oxides. A reduction of oxidic inclusions also occurs as a result of inclusion flotation from the liquid steel bath. This is assisted by gas bubbling when the inclusions can attach themselves to the bubbles by a surface tension mechanism. However, other significant developments in the latter half of the twentieth century included the use of vacuum metallurgy. Vacuum processes have been used to prevent oxidation of the molten metal either during melting, as a pre-casting treatment, or during the casting process itself and have also been used to de-gas the steel. Alloy steels in particular are very susceptible to hydrogen cracking and vacuum treatments proved extremely useful in reducing the hydrogen levels. The solubility of hydrogen (and other gases) is dependent upon the square root of the partial pressure of hydrogen and increases with increasing temperature. This applies to both liquid and solid steel but the slow rate of hydrogen removal in the solid state led to extremely lengthy hydrogen removal treatments (several weeks at 600–650°C). Hydrogen removal from the liquid steel is rapid provided that the necessary low hydrogen atmosphere can be provided. The reaction of oxygen removal involves the carbon content and the production of carbon monoxide. Reducing the partial pressure of carbon monoxide lowers the oxygen content of the steel at a given carbon content. The removal of both hydrogen and oxygen is
facilitated by the provision of gas nucleation sites, such as argon bubbles or exposed liquid metal surfaces. All of these requirements have been provided by a number of processes involving stream de-gassing, tank de-gassing or circulation de-gassing.

Tank de-gassing is affected by placing the ladle in a vacuum tank. Turbulence is produced in the liquid metal either by induction stirring or by argon bubbling. Bubbling causes a much greater turbulence under vacuum than is produced at atmospheric pressure, thus giving a much greater opportunity for intimate mixing of metal and slag, so that desulphurisation and de-gassing can be carried out simultaneously. Alternatively the ladle together with a fitted lid can form the vacuum chamber.

There are two main types of circulation de-gassers. The Dortmund-Horder (DH) system comprises a vacuum tank with a single refractory snorkel tube which is dipped into the ladle of molten steel. The steel is repeatedly sucked up into the vacuum chamber and released back into the ladle. The Ruhrstahl-Heraeus (RH) system has two snorkels which suck metal into the vacuum chamber and argon is injected at the bottom of one leg, inducing a circulatory motion of liquid metal between the ladle and the vacuum tank. These systems give very little slag disturbance in the ladle and do not therefore contribute to desulphurisation. However, Komai and Mizukami in 1982 developed a method for injecting a refining slag with the argon into the up leg of the RH vessel which proved very effective in desulphurising the metal.

Stream de-gassing essentially involves pouring a stream of metal through a vacuum chamber either into a second ladle or into an ingot mould within the vacuum chamber. The stream is broken into small particles of liquid as it meets the vacuum, thus providing very efficient de-gassing. This process, however, offers little scope for introducing other metallurgical control operations. The use of vacuum metallurgy includes vacuum induction melting (VIM) where the induction furnace is operated within a vacuum tank. This not only prevents oxidation from occurring but also leads to a very low oxygen content and clean steel by virtue of the low partial pressure of CO.

The time taken for refining in the ladle can result in significant heat losses even though some allowance may be made by increasing the superheat. In the late 1980s ladle furnaces were introduced in which three-phase electric power is supplied by three carbon electrodes in the same way as in the arc furnace. This heating compensates for the heat losses incurred during refining of the molten steel.

Another heating method which has been tried is the simultaneous addition of aluminium whilst blowing with oxygen. The exothermic oxidation of aluminium provides chemical heat to the steel, but this process has not found wide application. In 1989 Hoster obtained promising results with an AC plasma heating system using an argon plasma, thereby avoiding any possibility of the carbon contamination that may occur from carbon electrodes.

The intensive use of the ladle as an active refining vessel, together with arc heating or vacuum de-gassing processes, inevitably required improvements in
ladle refractories, particularly as demands for ever cleaner steels were imposed. One source of oxidic inclusions in the steel is the reaction between steel components and the ladle lining. The firebrick ladles of the 1950s have gradually been replaced by higher alumina bricks or by magnesite bricks. Monolithic dolomite linings are also used. These modern linings are more resistant to erosive attack by the steel and are economically viable because the long lives of the ladles more than offset the higher initial cost. Another significant development in the latter half of this century was the introduction of sliding gate nozzles which give far better control of the teeming stream than was obtained with the nozzle and stopper rod system.

An important development that can be classified as secondary refining is the AOD process, i.e. argon-oxygen decarburisation, for stainless steel manufacture. Until 1970 stainless steel was manufactured in an electric arc furnace. Decarburisation was effected by the introduction of oxygen but, at the low levels of carbon required in most stainless steels, the oxygen levels also resulted in oxidation of chromium with attendant chromium losses to the slag. Additions of expensive low carbon ferrochromium were then required to restore the chromium content. A reduction in the oxygen partial pressure and therefore the carbon monoxide partial pressure, by dilution with argon gas, can dramatically reduce the oxygen content in equilibrium with a given carbon content, thus minimising chromium losses and eliminating the need to use the expensive low carbon ferrochromium. The accepted method for the production of stainless steels is to melt the scrap mix or some cost optimised mixture of scrap, carbon steel, FeCr and Ni and then transfer the melt to the AOD vessel for refining. The very low carbon levels attained by this process route have virtually eliminated the need to use niobium or titanium additions as carbide stabilisers to prevent weld decay.

12.2.6 Consumable Electrode Re-melting
The consumable electrode re-melting process is not a primary steelmaking process. The feedstock is an electrode which has the essential chemical composition of the steel to be produced, having been made by a conventional steelmaking process. The cast and forged electrode is used to strike an arc on a baseplate within a mould. The baseplate has a covering of CaO–CaF₂ slag which melts and, being electrically conductive, is additionally heated by resistance heating. The electrode is gradually consumed and the liquid metal pool beneath it solidifies from the baseplate. The mould moves upward to contain the relatively shallow pool as the electrode melts into the pool and the pool freezes from the bottom. There are two forms of this process, the oldest being electroslag refining (ESR), sometimes known as electro-flux refining (EFR) and more recently vacuum arc refining (VAR). The processes give a product that has very little segregation arising from the selective freezing because of the small liquid metal pool and the directional solidification. The inclusion contents of both ESR and VAR steels are very low owing to the intimacy of the molten steel and the basic slag, and in the case of VAR to the vacuum melting, which reduces the oxygen content (and other gases) in the steel. These processes are
used to produce high quality highly alloyed steels for ultra-service conditions, and are generally termed secondary refining processes, the improved properties justifying the extra costs involved.

The ESR process was developed around 1940 in the USA but was first used commercially around 1960 in the USSR. The processes are now used widely in the production of high quality steels such as aircraft steels, rotor steels, bearing steels, etc. Developments in secondary steelmaking processes are producing very high quality steels and may challenge the use of the costly ESR and VAR processes in the not too distant future.

12.2.7 Casting Practice
The major steelmaking methods yield a liquid product which has to be solidified, formerly as ingots, but now in the form of semi-finished products such as blooms, billets or slabs. Significant developments have occurred in the tapping ladle as discussed earlier, including improved refractory linings to restrict erosion and the use of sliding gate nozzles to replace the stopper rod and nozzle that was used almost universally in the 1960s. Probably the most significant development in this area is the change from ingot casting to continuous casting. At this point it is relevant to draw attention to the studies made on the solidification of ingots and the formation of segregation in them. These commenced in the 1920s and resulted in the many reports of the ‘Heterogeneity of Steel Ingots Committee’ published by the Iron and Steel Institute over a considerable period, which stimulated much fundamental research into the solidification of liquid steel and the associated segregations. By the time that ingot technology was being displaced by continuous casting, a very thorough understanding of the processes of solidification and segregation had been achieved, and this knowledge was applied with advantage to continuous casting.

Since Huntsman’s invention of crucible steelmaking in 1743, molten steel had been cast into ingot moulds. When Bessemer developed his bulk steelmaking process in 1844 he also proposed the twin roll continuous casting process where liquid steel was poured into a narrow gap between twin rolls, emerging as a thin solid strip (see Chapter 1). Although Bessemer applied for a patent on this process in 1857, commercial steel manufacture continued with ingot casting for another hundred years. Goeransson had introduced the stoppered ladle in 1858 and this continues to be used today, although sliding gate nozzles have been used extensively since the 1960s.

Although Atha had developed a semi-continuous casting process for tool steel manufacture in 1910, the first fully continuous casting process has been attributed to Rowley in 1921 and involved strand bending and unbending. Problems with sticking and shell rupture were overcome by the introduction of mould oscillation in the Junghans-Rossi continuous caster. The first continuous caster of this type to be used for commercial steel manufacture was at the Allegheny-Ludlum Steel Corporation in the USA in 1947, several others being installed around the world in the early 1950s. Most of these early casters were used as pilot plants and the United Steel Companies team at Barrow, led by Iain Halliday, perfected the mould oscillation process using the concept of negative strip. Independent development work at
Low Moor Steelworks Ltd resulted in the introduction of mould powders for lubrication, thereby eliminating the need for conventional lubricants that had caused carbon pick-up in the steel surface.

Initial developments were based on billet casters but concasting was rapidly adapted to produce blooms and slabs. In order to reduce the hot working required for certain products the concept of 'near net shape' casting had been implemented. Following development work at BISRA in the UK, the first beam blank (BB) caster was installed at Algoma Steel in the USA in 1968. The beam blank mould produced a section that required minimal hot working to produce H-beams. The success of this operation led to the installation of two further plants in Japan by 1980 and by 1991 there were forty-three plants operating around the world. Thin slab casting using a tapered mould was undertaken at Allegheny–Ludlum in the late 1980s but the first commercial twin roll strip caster, i.e. the original idea of Bessemer, was installed in the Hikari Works in Japan in 1998. The Hikari caster is used exclusively for the manufacture of austenitic stainless steel strip.

Changing quality needs for steel have resulted in significant developments in the concasting process. Whilst the use of a tundish between ladle and mould was necessary to maintain the controlled flow of metal and allow changing of ladles without interrupting the metal stream, exposure of the steel to oxidation during ladle to tundish and tundish to mould pouring was overcome by inert gas shrouding of the stream and by using submerged nozzles.

The success of continuous casting is reflected in the extent to which it is used. By 1998, 84% of the crude steel output of the European Community and Western Europe was continuously cast. In Japan, 83% of crude steel output was continuously cast. In Eastern Europe the expansion of continuous casting has been much slower, only 18% of crude steel being continuously cast in 1988. However, it is likely that the present Japanese figure of 93% concast will be met worldwide as new plant is commissioned. The balance of the crude steel that is not continuously cast includes steel for the steel castings industry and special high quality low-volume steels manufactured in small amounts (10 tonnes or less). Recently horizontal continuous casting machines have been developed (1989) which avoid the need for the tall engineering structures associated with conventional casters. At present these are used exclusively for billet casting, but further developments are possible.

12.2.8 General Remarks
In this very broad overview of changes in ironmaking and steelmaking during the twentieth century it is not possible to include all the technical detail involved in a particular development. Variations in taphole location and design in arc furnaces, detailed methods of desulphurisation, control systems in blast furnace operation, control systems in continuous casting and the monitoring of chemical changes during pneumatic steelmaking, are but a few of these details. Also the scientific understanding of the processes has not been covered. The developments of thermodynamic concepts in the nineteenth and early twentieth centuries has required the determination of thermodynamic data for extensive application. This has
occurred in the twentieth century and a full understanding of the reactions has been obtained albeit with a degree of empiricism in the kinetic theories. Significant developments occurred in the 1950s and 1960s when techniques were evolved for temperature measurement and both liquid and gaseous flow measurements. These were used extensively in a diagnostic manner by Penghelly of the United Steel Companies Swinden Laboratories. Eventually cold simulation was introduced at these laboratories in the form of water models and air flow modelling. The final stage of this evolution was, of course, the now popular mathematical modelling which has been applied to a wide range of manufacturing processes involving heat transfer and chemical reactions. Computer programmes are now available for fluid flow systems and these are utilised extensively in tundish and nozzle design. These complex calculations are becoming an integral part of plant design and are important in understanding inclusion separation resulting from flotation and centripetal action. All these details are readily available in the vast literature on these and other subjects.

This broad overview has not covered all the manufacturing process now available for a variety of products. Processes such as vacuum spray deposition and hot isostatic pressing are capable of producing useful components but have been omitted from this section as they are essentially steel manufacturing processes. These are developments of the twentieth century and will fill niche markets, as will cerments, but the bulk iron and steel industry will be little affected by these developments.

13. DEVELOPMENTS IN MECHANICAL WORKING IN THE TWENTIETH CENTURY

The major mechanical working processes of rolling, forging, tube-making and wire drawing were established practices by 1900. The principles have remained unchanged but the scale of operations, productivity and dimensional accuracy have improved dramatically. Significant modifications have been made to the processing routes for wrought products.

13.1 Hot Working

13.1.1 Hot Rolling

Hot working was a rapidly developing area at the turn of the century, as outlined in section 4. Increases in productivity in rolling mills had been gained by the introduction of the three-high and reversing two-high mills and, although short sequences of tandem rolling were already in existence, an approach to the continuous mill had been made for small section and bar mills by the use of looping and cross-country mills. The main obstacle to fully continuous rolling mills was the need to control the roll speeds in order to compensate for the higher speeds required in successive passes as the sectional area of the stock was reduced and the
velocity of the stock increased. One of the major factors contributing to the development of continuous mills was the introduction of the electric motor, and its propensity for speed control and trimming. The fully continuous bar and rod mills were gradually developed with the stock being in several stands at the same time and never being free. In order to conserve space, alternate stands had vertical rolls thus eliminating the need for bar twisting between passes. These continuous mills naturally showed high productivity.

The first electric motor driven reversing mills for bloom, slab or plate rolling was introduced in the USA in 1915. At that time all such mills were steam powered but afterwards no new steam powered mills were installed. In the hot rolling of strip, the major development in the twentieth century has been the increase of strip width. In 1900 the maximum width of thin hot rolled strip was about 250 mm. By 1925 it had increased to 925 mm and in 1969 it was about 2,500 mm. An empirical approach to hot strip rolling had been applied prior to 1920 in which it was considered that the width to thickness ratio should not exceed 150. In 1926 a hot strip mill was built in Pennsylvania which combined four-high finishing stands, tandem rolling in the finishing stands, and hot coiling equipment at the discharge end. This was the first of the modern hot strip mills so widely used today. Although economics might suggest that narrow strip should be obtained by slitting wide strip, narrow strip mills find a market because of the advantages of a rolled edge rather than a slit edge.

The increased width of strip required longer rolls, which result in greater roll flexing. Increases in roll diameter to prevent roll bending resulted in higher power requirements, but the four-high mill, having smaller work rolls and large back-up rolls, largely overcame the roll bending and high power problems. Excessive roll bending gives rise to 'crown' on the strip profile (thicker in the centre than at the edges) and a further step taken to reduce this was the use of cambered rolls. Strip flatness is very important for materials which are to be cold rolled to thin strip. In the 1960s back-up rolls were flexed elastically to counter the roll bending caused by strip rolling.

An alternative for the production of hot strip was the planetary mill, introduced in the 1960s having a pair of large diameter rolls with numerous small rolls around each. The planetary mill is capable of reducing the slab to finished strip thickness in a single pass owing to the sequential action of the small planetary rolls. Although some planetary mills are still in use, the bulk of hot rolled strip is produced on the more traditional four-high mills and the planetary mill is generally restricted to the production of high alloy steels. The production of hot rolled sections were well advanced by 1900 and the main change observed since then is an increase in the size and length of sections produced. By 1983 structural sections (H-beams) some 86 m in length could be produced, which were subsequently cold sawn to length. The hot working processes associated with seamless tube has likewise changed very little since the turn of the century although improvements in, for example, the materials used for mandrels, have taken place.

Probably the major change that has occurred in the twentieth century concerns
process control. With the introduction of modern mills, process control has become an integral part of these systems, as is discussed in a later section. These systems include the control of the rolling variables to produce desired microstructures and the control of the post-rolling cooling rate. Consider for example the manufacture of hot rolled strip. The mills are rolling faster and the stock is finished hotter for any given reduction and section size. Coiling had been introduced to obviate the need for excessively long run-out tables and cooling systems were introduced just before 1950 to reduce the coil temperatures and prevent inter-lap welding, without increasing the mill length unduly. The cooling systems have become increasingly sophisticated and include water sprays, laminar flow cooling (developed in 1957 and applied in 1962) and more recently window cooling (1980s), the latter two being claimed to extract heat from the strip more efficiently than does spray cooling. Examples of each of these systems can still be found. The features of these mills were initially based on the economics of rolling, but have proved to be invaluable as metallurgical tools for microstructural control, particularly with the introduction of micro-alloyed steels. Hot rolling finishing temperatures can be controlled by introducing delays between roughing and finishing trains, whilst the transformation of austenite to ferrite (and the attendant precipitation of micro-alloy carbides) can be controlled by changes in cooling temperature effected by changing the amount of cooling water applied between rolling and coiling. Such effects proved particularly potent in rolling titanium micro-alloyed steel where the yield strength of the hot band could be varied from 320 N mm\(^{-2}\) to 700 N mm\(^{-2}\) by changing the cooling temperature.

The qualitative effects of low finishing temperatures and grain refinement were appreciated at the turn of the century but the deliberate and quantitative control of processing variables designed to produce specific microstructures and properties, such as are implied by the term controlled rolling only commenced in the 1960s. Controlled rolling and controlled cooling were not confined to hot strip products but extended across the whole range of hot-worked products. Controlled rolling of plate was practised to give grain refinement and improved toughness in the product. Controlled cooling of plate has been practised both after a normalising heat treatment or after controlled rolling, to refine the transformed microstructure, using air blast or water spray cooling. A more extreme case of controlled cooling is to be found in the direct quenching of hot rolled plates, developed in the 1980s. This process uses the sensible heat of the hot rolled product and eliminates the need for off-line heat treatment, thereby conserving energy and conferring an economic advantage. The use of such extreme cooling necessitates a quenching press to prevent undue distortion of the plate product.

In the manufacture of large H-beams, selective spray cooling has been applied to the heavier section junctions between web and flange. Properly applied, this procedure gives a more uniform cooling rate, minimising distortion, but also improving the microstructure and properties in the web/flange junction. In the manufacture of rails, retarded cooling has been used since 1937 to prevent hydrogen cracking of the rails, but in the 1980s head-hardened rails were pro-
duced by forced air cooling of the head after induction heating to 900°C. The surface microstructure is thus modified to give more pearlite with a finer interlamellar spacing than is observed after normal air cooling, and the hardness is increased to 400 HV compared with the normal level of 280 HV. The fatigue limit and wear resistance are thus improved without the need for increased alloy content.

Controlled cooling is also used to good advantage in the rod rolling of low carbon steels for wire manufacture. Modern rod mills with their high speed rolling give relatively high finishing temperatures, as the heat generated by deformation is not dissipated by interstand cooling or roll chilling; such rod is normally coiled and cools at a rate controlled by the size of the coil.

In the 1960s the Stelmore process was introduced where the hot rolled rod is 'laid' in an open spiral, so that the cooling rate is controlled by the bar diameter. Further, the 'laid' spiral is passed under a hood with a forced air draught which enhances the cooling. The structures formed in the rod are very similar to those produced by air-patenting, thus improving the drawability of the rod without incurring the cost of patenting. There were about fifty such systems operating worldwide in the 1980s.

A novel controlled cooling system for reinforcing bar was developed at CRM in Liege in the 1970s, known as the Tempcore process, whereby the bar on leaving the last rolling stand is immersed in water by passing through a trough. The time of immersion is sufficient to quench only the outside of the bar. As the bar emerges from the water trough, the residual heat from the inside tempers the surface martensite produced by the quenching operation. Thus the inside of the bar shows a normal ferrite–peralite structure whilst the outer region comprises mainly tempered martensite. The strength of these Tempcore bars is high, and this is accompanied by a high level of toughness. The process has attracted only limited application.

Attention was also given to other factors controlling the economics of rolling. In the 1970s high alloy work rolls were introduced thus allowing longer runs of a particular product and reducing the time lost by reducing the frequency of roll changing. In the 1990s high speed steel rolls were introduced into hot strip mills in Japan and at Sollac in France. In the 1980s direct charging of hot billets, blooms or slabs into hot mills was introduced which not only gave economic benefits but also responded to conservation and environmental pressures for the reduced use of fuel. Also, direct feeding from the concast machine into the hot mill was tried at this time. There is no doubt that such procedures are soundly based, but some form of interval is required to allow temperature equalisation across the section in order to give uniform deformation and good control of product dimensions. These procedures have not been applied universally at the present time. In 1996 Kawasaki in Japan introduced endless rolling, with the head of one strip being welded to the tail end of the previous strip to maximise mill time.
13.1.2 Hot Forging
Dramatic strides had been made in forging during the nineteenth century with the introduction of the steam hammer in France in 1842, the hydraulic press in the UK in 1861 and the double-acting steam hammer in the USA in 1888. Increases in power led to increased usage of broad, flat, tooling with its improved efficiency in closing central looseness in ingots. From the standpoint of forging equipment the rotary forge was introduced around the middle of the century. This forge has two sets of opposed dies in the forging head which are activated mechanically. It operates at much higher speeds than the steam hammer and is capable of a high degree of precision, thereby reducing subsequent machining costs and is also easily adapted to programmed shaping of the forgings. Mention has been made previously of hot isostatic pressing.

13.2 Cold Working

13.2.1 Cold Rolling
In the late nineteenth century cold rolled strip was being produced in two-high mills stands, Fig. 4(a), in limited lengths. Roller bearings had been introduced in
1890 to reduce wear of the roll necks and the first cold strip reeler had been introduced at the August Schmitz Co. in Germany. The early advances in cold rolling were aimed at increasing the throughput of the cold mill. The first innovation was to use mill stands in tandem and in 1904 the first tandem mill was introduced comprising four two-high stands. The rolls were powered with independent adjustable speed electric motors. The first high tension reeler was patented by Conklin in the USA in 1905 and in 1915 tension reelers were used in conjunction with the tandem mill. The tension reelers contributed to lower mill loads and the maintenance of dimensional control.

Patents on reversing cold mills were taken out in Germany as early as 1917 and a reversible two-high mill was in use (Fig. 4(b)). The reversing mill increased productivity by reducing coil handling between passes and, by leaving the end of the coil unrolled, considerable time was saved in coil end manipulation. The thick unrolled ends of the coil were discarded.

As the customer demands had led to increased strip widths, as described for hot rolling, roll bending and crown on the strip naturally increased. This led to the introduction of the four-high mill at the Allegheny Steel Corporation's Works in the USA in 1923 (Fig. 4(c)) and roller bearings on the back-up rolls were applied in 1926. Reversing four-high mills appeared in Germany in 1923. As the strip dimension became wider and thinner, the power requirements were high owing to the substantial size of the work roll. The four-high mill could be used, but reductions in work roll diameter with the four-high roll configuration led to roll flexing in the horizontal plane and, when substantial backing rolls are in place, the lateral flexing of the work roll allows crown on the strip. This problem was addressed by the introduction of cluster mills. Rohn in 1925 had devised cluster mills with 10–18 rolls per stand. These comprised two work rolls, intermediate rolls and large diameter back-up rolls, as indicated in Fig. 4(e) and (f). The early Sendzimir mill developed in Poland in 1932 had six rolls per stand, i.e. two work rolls, each with two back-up rolls as shown in Fig. 4(d). It will be appreciated that the minimum diameter of the work roll is limited by the geometry of the roll disposition and the necessary stiffness (large diameter) of the back-up rolls. In the 1940s the Sendzimir mill developed to a twelve roll system, i.e. two work rolls, four intermediate rolls and six back-up rolls (see Fig. 4(e)). A parallel development produced the reversing Y-mill in the late 1940s, so called because of the disposition of the back-up roll centres (Fig. 4(f)). The small size of the work rolls required a high level of wear resistance and WC work rolls were used in this configuration. Further developments of the Sendzimir mill occurred and in the 1950s a twenty roll stand was used. The complexity of the roll arrangement and the need for rapid roll changes led to the development of the Cartridge mill in the 1960s where a single assembly (cartridge) of rolls could be inserted into the mill stand. The sophistication of the cluster mills should not be taken, however, as a measure of their popularity; very often they are used for special steels and the common strip steel grades are generally rolled in the more conventional four-high mills. These developments in rolling mill equipment were largely completed in the mid 1960s and achieved their aims of minimising...
mills, increasing productivity and improving dimensional tolerance and flatness.

A very significant development occurred in Japan in 1969 when the Nishin Steel Co. installed the first fully continuous mill with head to tail welding of stainless steel coils. Using strip accumulators, it was possible to keep rolling the strip drawn from the accumulator whilst the tail end of that coil was stopped to be welded to the head of the next coil. After welding, the stock of strip in the accumulator could be built up by running the new coil faster until there was sufficient stock for the next welding operation. The significance of this development was that it opened up the entire field of continuous on-line processing, with combined pickling and cold rolling being introduced in Japan in 1986.

Almost all the cold rolled strip manufactured is first cleaned electrolytically in an alkaline bath and then annealed to produce a softer more ductile and formable material. Bulk steel softening involved batch annealing furnaces operating at temperatures of 700°C maximum to avoid serious interlap welding. This was a slow process as the massive coils required lengthy heating and soaking (150 h) to allow temperature equalisation throughout a 10-20 tonne coil. Even after temperature equalisation, there was significant variation in the microstructure and properties owing to the differences in time at temperature between the outer laps and the inner laps of the coil. In 1963, open coil annealing was introduced where the tight coil was re-wound using a wire, or similar, spacer between each lap. The diffusion of heat was thus improved by effectively reducing the thermal diffusion path to the strip thickness rather than the coil dimension. The more rapid heating and cooling dramatically reduced the annealing cycle time and, by controlling the furnace atmosphere, decarburisation and nitrogen removal could be effected, thus further improving the formability. This process is still essentially a batch process.

Continuous annealing, although long used for special steels such as stainless and electrical steels, was introduced for tinplate manufacture in 1963, where the strip is passed into the heating zone of the furnace, being fed from the cold rolled coil and re-coiled on exit from the cooling zone of the furnace. This simple treatment was adequate for the limited formability requirements of tinplate, but in the next 10-20 years more complex thermal cycles were developed.

The change from batch annealing to continuous annealing required an intense effort in establishing the processing conditions required for highly formable steels to be continuously annealed, as even the hot rolling and cooling cycle influences the properties of the cold rolled and annealed steel, and the optimum conditions were found to be very different from those pertaining to the formability of cold rolled and batch annealed strip. The more complex annealing cycles in modern continuous annealing lines involve heating to the annealing temperature, primary cooling, heating to an overageing temperature and final cooling, in order to control the interstitial contents and give optimum formability. The concept of in-line continuous processing took a significant step forward when in 1988 a line was installed and operated at Nippon Steel Corporation, Japan, in which the hot rolled coils were head to tail welded and the strip pickled, cold rolled and electrolytically cleaned,
continuously annealed using the dual thermal cycle, temper rolled and re-coiled. Individual coils were re-formed by an in-line shear after the temper rolling treatment. Thus the hot rolled strip is converted to high formability cold rolled and annealed strip in a single operation.

At the turn of the century, hot dip galvanising and tinning processes were already in use to provide corrosion resistant material, but were largely applied to cut sheets or manufactured components. Much development has occurred in the area of coated strip in the course of the past hundred years.

The hot dipped tinplate process underwent a considerable change with the development of continuous strip cold rolling and coiling. The hot dip procedure also was modified to become a continuous process in the early 1930s, producing a more uniform product by virtue of the dynamics and continuity of the coil feed into the tin bath. Until 1937 all tinplate was produced by the hot dipping process where either cut sheets or continuous strip were fed into the molten tin bath. The possibility of electrolytically depositing tin on iron or steel surfaces had been known for a considerable amount of time but had not been applied to the coating of cut sheets owing to handling and control difficulties. With the introduction of continuous cold strip, however, and its use for continuous hot dipping, interest in the possibility of a high speed continuous electro-tinning process was re-kindled. In 1935 small pilot units had been constructed to investigate the electro-deposition process on a rapidly moving continuous strip. Electrolytic tinplate was available as a commercial product by 1937. The electrolytic tinplate, as deposited, was dull and semi-lustrous and, although attempts were made to control the surface appearance by adjusting the electrolysis conditions, a rapid heat treatment which melts the tin deposit and allows the development of an alloy layer, provides the bright lustrous surface so characteristic of hot dipped tinplate. The success of the electrolytic process can be judged from its increased usage. In the late 1940s the tonnage of electrolytic tinplate had surpassed that of hot-dip tinplate and by the late 1960s almost all tinplate was produced electrolytically.

The high price of tin and its limited availability at certain times has led to a number of developments either to improve the corrosion resistance of the surface and reduce the coating weight, or to reduce the coating weight on one side of the strip. Improving the corrosion resistance of the surface has been achieved by lacquering or by the deposition of a very thin passivating chromium-chromium oxide layer on the tin oxide surface. In 1966 the chromium-chromium oxide layer was used without tin, the product being known as tin free steel (TFS) or electrolytically chromium coated steel (ECCS). The tin free steel usually requires lacquering but has satisfied up to 15% of the traditional tinplate market.

Similar changes have occurred in the history of hot dip galvanising, i.e. hot dipping of sheets and products, continuous hot dip galvanising and electro-galvanising. Steel producers have traditionally worked closely with their customers in order to identify customer needs and develop products suited to them. Bearing in mind the extremely diverse nature of the myriad applications of steel, this is no mean task. In the late 1980s the British Steel Corporation installed a canning line for
the development of can-making procedures for evaluation of tin mill products and
assessment of the suitability of such products for newly developed food products.
In other areas, close liaison with the automobile industry led to the development of
a one-side galvanised product, putting the corrosion resistance on the side where it
was needed but conserving zinc and product weight. The one-side zinc coating was
facilitated by the existing electro-galvanising lines. With advances in joining tech-
nology, such as laser welding, the development of automobile strip is continuing
and trials have been completed in the study of joining one-side galvanised strip to
forms of strip with or without other protective coatings. Such composite strips can
be used for the manufacture of, say, door panels where a high formability require-
ment of one part of the panel can be combined with a high corrosion resistance of
another part of the same panel. Given the developments in the coating and form-
ing technologies, the permutation of strip products and properties becomes
immense. Organically-coated strip is considered in a later section.

13.2.2 Other Cold Working Operations
The manufacture of wire by cold drawing is an ancient process and was well devel-
oped at the turn of the century. The use of tungsten carbide dies commenced in
1929 and gave reduced die wear. The tungsten carbide die is now almost universal
apart from the use of diamond dies for the smaller sized wires. Over the twentieth
century there have also been progressive improvements in the surface coating of
wires, e.g. galvanising.

The improved understanding of the transformation of austenite during cooling
led to the adoption of patenting practices particularly for high carbon steels. Lead
patenting involves an austenitising treatment at temperatures above those used for
normalising, in order to give a slightly coarser austenite grain size and retarded
transformation of austenite, followed by quenching in a lead bath held at a suitably
low transformation temperature to give a fine pearlite structure. The fine pearlite
structure imparts improved ductility for the drawing process whilst at the same
time giving improved strength at any given drawing reduction.

The austenitising treatment also has been carried out in a high temperature lead
bath, the process being known as the double-lead process. Prior to the lead patent-
ing process, air patenting was used in which the strand of wire was fed through a
furnace to effect the high temperature austenitising treatment and then cooled in
air on emerging from the furnace. The rapid cooling rate obtained for the strand of
wire was sufficient to cause low temperature transformation to produce a fine
pearlite structure, although the most consistent structure with the highest strengths
are obtained by lead patenting. In recent years, there has been a trend towards the
old air patenting treatment, to reduce the processing costs and avoid the toxicity
problems associated with lead baths. Controlled cooling during the manufacture of
wire rod, as in the Stelmore process described previously, has been used to elimi-
nate the need for an initial patenting treatment.

In the manufacture of tubes the concept of continuously butt welded pipe was
proposed in 1911 by Moon. The first commercial production of continuously butt
welded pipe occurred in 1922 and was carried out by the Fritz-Moon Co. This involved the cold bending of strip into tubular form with fusion butt welding being carried out on the seam of the emergent cold formed tube. Electric resistance welding was also used to close the tube seam. Various welding processes were introduced to manufacture seam welded stainless steel tubing.

13.3 Automatic Control and Process Simulation

A notable feature of all modern ironworks and steelworks is the degree of automation and automatic control. A wide variety of sensors have been developed ranging from the well-known radiation and bi-metallic pyrometers to chemical sensors for specific element concentrations, load cells, X-ray thickness measurement and laser beam sensors. Such sensors offer continuous and rapid response measurements that can be linked to a control system which may either give warning of unexpected deviations or take corrective action to eliminate such deviations. When such systems are coupled with computers, programmed processing becomes possible, provided that the necessary systems and control principles are in place.

In the course of the programming of any given process route, a detailed knowledge of the material behaviour is required and a strong feature of work in the twentieth century has been the provision of detailed behavioural responses for both machines and materials. This is very evident in the field of the mechanical working of steel where the science base of the thermal properties of steels, the mechanical properties over a wide range of temperatures and the metallurgical effects of deformation, recovery and recrystallisation have been extensively documented. Such principles have been incorporated into expert systems, capable of offering drafting schedules to limit mill loading and power consumption, and equally capable of predicting dimensional changes such as spread, and predicting the evolution of microstructure during and after multi-pass rolling. Such systems appeared in the 1970s and are becoming more refined with increased absorption of the scientific principles. The increased power of computers enables a much broader data base to be incorporated and, together with finite element procedures, is capable of providing more precise predictions of mill loading, temperature distribution in the stock, and spatially distributed microstructural changes, e.g. surface to centre variations. This work will undoubtedly continue into the next century and will provide the basis for the development of optimised processing routes. The same philosophy will be applied to all aspects of steelmaking, ironmaking and processing.

It can readily be appreciated that the development of the continuous mills, automatic control of roll speeds and shear, product size and shape, has led to a considerable reduction in manpower requirements. No wonder that our 1900 metallurgist would find the modern rolling mill a strange place. Not only is there a notable absence of workers on the mill floor but the control of the whole mill can be conducted from a remote control room where even the mill operation is viewed by closed circuit television!
14. HEAT TREATMENT IN THE TWENTIETH CENTURY

This section will deal mainly with conventional heat treatment. The many processes now described as surface engineering will be considered in a separate section. Also, although certain continuous heat treatment processes such as controlled cooling, continuous annealing etc. may be mentioned, these have been discussed under the heading of mechanical working developments.

14.1 Heat Treatment Equipment

Early in the twentieth century the furnaces used for heat treatment were predominantly gas fired with relatively unsophisticated temperature control and measurement, visual comparisons with arbitrary standards are often cited. Uniformity of heating was problematical and the methods of cooling were simple, comprising furnace cooling at a rate dependent on the furnace thermal and charge characteristics, air cooling at a rate governed by the dimensions of the material, oil quenching in an oil of unknown thermal and physical characteristics, water quenching and brine quenching. Because of the absence of atmosphere control during heating, scale and decarburisation was present and uncontrolled, and the presence of oxide scale made reproducible quenching rather difficult. Relatively small masses of components could be handled easily. Tempering was used widely on hardened products and an early form of patenting treatment for wire was available, but not isothermal patenting. In fact the understanding and control of heat treatment was very much in its infancy and was rather an art!

With the rapid development of electrical generation industries, especially in the 1920s, electric heating became ever more common, although even at the end of the twentieth century there are still some gas fired furnaces. Major advances were made in ensuing years in terms of the uniformity of temperature distribution in furnaces and the developing technology of pyrometry enabled accurate temperature measurements to be made whilst the invention and development of temperature control equipment made reproducible heat treatment cycles a practicality. After 1945 controlled atmospheres were used increasingly and were often of a synthetic nature, to prevent oxidation and decarburisation. The composition of the atmosphere was controlled often by its dew point and quenching under the atmosphere was developed with gas curtains to prevent air ingress. The tendency for cracking during heating for hardening was decreased by uniform heating and particularly in the case of high alloy and high carbon steels by control of the heating rate.

The need to prevent quench cracking and minimise distortion during quenching was addressed by attention to the quenching media following the work of French (1930) and Russell (1936) on the rates of cooling over various temperature ranges in different quenchants. This led to the concept of severity of quench, itself an integral part of the technology of hardenability. Many quenching media of differing characteristics were developed, particularly oils, and more recently water-polymer sol-
utions. In order to obtain uniform quenching, agitation systems were introduced which produced high agitation near the charge input point and less agitation further into the system. As the quenchant increases in temperature with continual use, its characteristics alter so that pumping of the quenchant through a cooling system was introduced to keep the quenchant temperature constant. Also in polymer-water quenching media, control of polymer concentration, temperature and agitation is necessary for consistent characteristics. Distortion owing to transformation strains and thermal stresses during quenching has been addressed and made more consistent by the use of quenching dies, jigs and presses and roller quenching.

Other methods of heating for heat treatment have been introduced to increase the speed of austenitisation, minimise decarburisation and give more uniform heating. These comprise such methods as electrical resistance, induction heating, fluidised beds, salt baths, etc., but despite these the majority of components are still heated in what may be regarded as conventional furnace equipment.

14.2 Heat Treatment Processes

The conventional heat treatments of full annealing, sub-critical annealing, normalising, quenching and tempering have been used throughout the twentieth century, albeit with an ever increasing understanding of the metallurgy which underpins them and of their effects on the microstructures developed. They still form by far the most widely used heat treatment processes today.

A few comments on some of the refinements introduced may be relevant. Annealing at high temperatures, well above $A_3$, has been used to homogenise segregations, but the process is so slow that it is rarely used except in very special circumstances and invariably requires a further heat treatment, if only to refine the grain size. Invariably a more efficient homogenisation treatment is to hot work the steel where this is practicable. Spheroidising, conventionally by sub-critical annealing just below $A_1$, has been supplemented by repeated heating and cooling into the critical range, and in high carbon hypereutectoid steels by cooling slowly from just above $A_1$, where the pre-existing carbides act as nuclei for the growth of spheroidised carbides during cooling through the pearlite transformation to produce 'divorced' pearlite. Some treatments have used heating to within the critical range followed by rapid cooling, which by partitioning can produce structures of ferrite and austenite/martensite. These dual phase structures have improved stretch formability and are reported to have better resistance to intergranular caustic stress corrosion cracking than for example, a ferrite/pearlite structure. The use of these structures is very limited and has belied their promise as a formable steel in the 1980s.

Possibly the original form of intercritical heat treatments in the 1940s was applied during the tempering of 9%Ni steels, which have very low $A_1$ temperatures, to produce structures of tempered martensite and inter-lath retained austenite. Such structures have very good low temperature toughness, improved further by the nickel content and the same principle has been used but to a very limited
extent, in the ultra-high strength martensite/retained austenite steels, the duplex steels. Another form of annealing has been the dehydrogenisation treatment below the $A_t$ for large forgings in material subject to hydrogen embrittlement. The process is lengthy and expensive and usage has reduced because of degassing treatments during modern steelmaking which reduce hydrogen contents below the threshold for hydrogen cracking. The ultra-low sulphur contents produced by modern steel-making practices can, however, lower the hydrogen threshold for embrittlement, so care is advisable.

Normalising treatments, i.e. air cooling from just above $A_3$, have been used through most of the twentieth century but possibly to a lesser extent in recent years, as advantage has been taken of the fine grain size produced both by grain size control and controlled thermo-mechanical working to allow an on-line normalising treatment. Double, or even multiple, normalising has also been used to improve the mechanical properties of large cast products and heavy forgings, but again is no longer necessary in modern grain refined products, except in thick plate where normalising is mandatory.

Quenching in oil or water has been used since earliest times, but with little understanding of the metallurgical science involved. An understanding of the nature of martensite in the 1920s and 1930s and particularly the advent of the concepts of isothermal transformation and hardenability in the 1930s, enabled a rapid application of scientific principles to quenching. Especially the work on hardenability enabled the relationship between hardenability and quenching conditions to be exploited to allow not only optimisation of steel composition but also the optimum severity of quench for the required strength and hardness distribution across the component, whilst minimising distortion and quench cracking. Various novel quenching processes such as spray and mist cooling were tried but never became popular except for very special applications.

Direct quenching of hot worked or formed components is one form of energy efficient processing, especially in fine grained steels which provide improved toughness. The effect of the fine austenite grain size in decreasing hardenability has to be offset by an increased severity of quench. Deliberate use of slack quenching or quenching on a falling temperature gradient has sometimes been used, but rarely in view of control difficulties. Of particular interest has been the use of sub-zero refrigeration after quenching to transform retained austenite in steels with $M_f$ temperatures below room temperature. This was to transform the retained austenite to martensite prior to tempering and has been especially used in hard materials which are tempered at low temperatures, e.g. tools, gauges, cold rolling rolls, etc. because the retained austenite became stabilised as the cooling rate decreased in the later stages of quenching. Such stabilised retained austenite was reluctant to transform at the low tempering temperatures used but did transform to untempered martensite during use, leading to distortion, dimensional instability and, in extreme cases, to catastrophic (even explosive) cracking.

After 1930, the principles of isothermal transformation were applied to heat treatment processes. Mention may be made of isothermal annealing by cooling the
austenite to just below $A_1$ and allowing it to transform. This is cost effective as it allows the material to be air cooled after transformation is complete rather than for furnace cooling to be continued. Process times are thus considerably shortened. A variant of this has been the lead patenting process for isothermally transforming wire before drawing and as an inter-pass treatment. Other processes based on isothermal transformation are martempering, which allows martensite to form at slower cooling rates and, in the absence of a temperature gradient from surface to centre of the component, is used to minimise distortion and quench cracking, whilst austempering is used to form bainite which can have properties not too dissimilar from those of tempered martensite, but without the use of a separate tempering treatment. However, martempering and austempering are restricted to certain steel compositions of appropriate transformation characteristics. Double quenching treatments, or repeated heating treatments have been used, but these processes have rarely been applicable to conventional industrial heat treatment.

The basic process of tempering has not altered in principle since well before 1900, but the understanding of the mechanisms involved has increased greatly and especially the embrittlement processes which occur in different tempering temperature regimes. One of the most interesting innovations was the use of a homologous tempering parameter combining both the tempering temperature and time (Holloman and Jaffe, 1945). By plotting hardness or strength against this parameter, a large amount of tempering data can be represented by one ‘master’ tempering curve, even for alloy steels which show secondary hardening. Moreover it is possible to calculate how the tempering temperature and time can be altered without changing the hardness or strength. This approach can be used to avoid, for example, a particular embrittlement temperature range and the idea has been extended more recently (1980) to enable it to be applied to production heat treatment where the temperature may change or tempering may be repeated, or in which tempering is occurring during heating or cooling. It is possible that in future a similar approach may be able to predict property changes owing to microstructural degradation in materials operating at high temperatures, e.g. creep resisting steels. Certain steels such as bearing, tool, creep resisting and hardenable structural steels have in certain circumstances been double tempered. This may be applied to eliminate retained austenite or to increase microstructural stability. However, if there are different carbides formed during the two tempering treatments, some loss of toughness has been sometimes observed.

In general, double tempering has never been widely accepted and remains a little used conventional heat treatment. Perhaps the most important advance in heat treatment since about 1950 has been the very economical conservation of sensible heat by performing the heat treatment directly following hot working, such as for example in the direct cooling of forgings, direct quenching which has already been mentioned, and controlled cooling after thermo-mechanical working of rod, bar, strip and plate. This subject has been discussed elsewhere.
15. WELDING DEVELOPMENTS IN THE TWENTIETH CENTURY

15.1 Welding Process Developments

Forge welding by blacksmiths has been used since antiquity and was used even at the start of the twentieth century in the manufacture of some tubular products. Rivetting, however, was the most common joining method, even into the 1930s, the Sydney Harbour bridge and virtually all ships being rivetted, but the process was uneconomical in terms of time and material usage (overlapping plates for example) as well as allowing crevice corrosion and thus requiring constant protection by painting, etc. Modern welding can possibly be dated from about 1880 when locally generated heat for melting by flames, electric arcs or resistance heating, became available. For example, oxy-acetylene and arc welding developed basically from sources originally used for lighting. Oxy-acetylene welding was first used practically in 1901–1903. The first carbon arc welding was in Russia in 1881–1885, but was fairly rapidly replaced by bare metal arc welding in both Russia and the USA. Coated steel electrodes for metal arc welding originated in Sweden in 1907 (Kjellberg), the first coating being lime, but by 1909 Strohmenger produced a very successful coating, used for many years, by winding blue asbestos string around the wire. This is an interesting commentary on the awareness of health hazards in the early 1900s. Nevertheless bare metal electrodes were in limited use until the 1930s, but weld quality was poor and the use of flux coatings on the electrode was introduced to provide an evolved gas shield for the arc and a slag covering for the molten weld pool. The common coatings were cellulosic, rutile or basic calcium carbonate/calcium fluoride.

Cellulosic coatings decompose during welding to produce a protective atmosphere of hydrogen leading to a high hydrogen weld metal and relatively little slag cover. Hydrogen heat affected zone cracking was a problem as it also was with rutile coatings, which produce relatively high hydrogen weld metals and diffusion of hydrogen into the heat affected zone. Basic coatings give low hydrogen contents, but to do so must be dried prior to use, often at quite high temperatures of several hundred degrees celsius. Basic coatings, which became (and are) widely used, also produce a well fluxed, clean molten pool and good quality welds very suitable for the higher tensile strength steels and complex, highly restrained joints. These coatings could also contain iron, deoxidants and alloying elements which enabled control of weld composition. For stainless steels, stainless core wires were used after about 1920, either of very low carbon content or containing Nb as a carbide stabilising element; titanium does not transfer readily through the arc. Other welding processes were also developed, namely the thermite process in Germany by Goldschmidt (1900–1902) and electric resistance welding by Coffin in the USA (1887). All these processes were invented prior to about 1914, and have been called the 'old' welding processes by Houldcroft (1991) and included electric resistance welding such as spot, seam, butt and flash welding.
By about 1935 their potential was recognised and they rapidly replaced rivetting as a joining process. They were in large scale production from 1935 onwards and are widely used today. Prior to 1939 certain naval vessels were of largely welded construction and welding was also introduced progressively into civil engineering. During 1935–1945 mechanical methods of using electric arc welding were developed, such as submerged arc welding in which a flux was separately introduced to a continuous arc welding configuration, and cored hollow electrodes containing the flux and alloy additions. During the Second World War, welding, and particularly electric arc welding and the mechanised methods, played a crucial role in war production where material conservation and speed of production were at a premium. In the steel area, particular mention should be made of armoured fighting vehicle manufacture and especially ship building. This latter was greatly accelerated by prefabrication methods to give remarkably short keel to launch times. But some significant problems arose, not least of which was catastrophic brittle fractures arising from poor welding and the associated defects, together with a fracture-prone microstructure.

The obvious success of welding during the war led to a period of intense research after 1945 in which many countries established welding research organisations and professional institutes devoted solely to welding phenomena. Many of the cracking problems associated with welds and heat affected zones were intensively investigated and in many cases eliminated, as will be described later. Metallurgical, scientific and engineering principles were applied to welding technology (Easterling, 1983) and many new ways of generating heat were investigated and exploited, often for rather specialised applications.

The period 1945–1970 was the time in which what Houldcroft calls the ‘new’ processes were developed. These cannot be discussed in detail in the space available. They included such processes as gas metal arc, inert gas tungsten arc, electroslag, friction, diffusion, explosive, plasma, ultrasonic, spot, seam and flash welding, electron beam and laser welding. A few brief comments can be made. The well established older processes, e.g. manual metal arc and submerged arc, still remain the mainstay of welding today, whilst the newer processes mentioned above often have been used for special applications requiring very high quality welds of awkward configuration in steels which in the 1950s would have been very difficult to weld. The gas metal arc and inert gas tungsten arc processes use shielding gases of argon, helium or CO₂, the latter not being used for stainless steels due to possible carbon pickup. These can produce autogenous welds or use a filler wire, the tungsten electrode being non-consumable. Plasma welding concentrates the arc and can be deeply penetrating, often completely with a keyhole technique, the underbead being very smooth, an advantage for inaccessible undersurfaces. These are precision techniques and tend mainly to be used on thin, special, materials where high quality is essential. Spot, seam and flash welding are all variants of electrical resistance welding, and are readily applied to steels. Lapped joints are often made by spot and seam welding, the main use being in automobile bodies, domestic equipment, food cans, drums, etc. Flash welding is also used for bars, shapes, tubes,
rings, automobile wheel rims, etc. and dissimilar metals can be joined, for example mild steel to high speed steel for drill blanks.

Solid phase welding, such as friction welding, is almost a modern type of forge welding; it can produce high quality welds and is readily adapted to an automated production line. This is not the case for diffusion welding, however, which has relatively limited use. Other solid phase welding methods, such as ultrasonic and explosive welding, are rarely used for steels. Power beam welding by electron or laser beams also are rarely used for steels, except in special circumstances, but interest in laser welding has recently been expressed because of the very small HAZ. Electron beam welding requires a high vacuum which generally limits the size of component, or is relatively inconvenient for larger assemblies in which the work has to be moved in and out of a work chamber. Laser welding can be done at normal pressures but the vapour in the welding cavity must be dispersed by gas jets as it is opaque to laser light. Laser welding has been used, however, to join sheet or strip during continuous processing. Electroslag welding is applied to steels for cladding and the repair of worn surfaces.

Since the 1970s the pace of invention and development of novel welding processes has abated but there have been considerable refinements of equipment aimed at improving performance, productivity and the quality of the welds. Particularly, progress has been made in control and automation, and in the use of robots. Computer control of welding installations, using complex operational sequencing necessary for automated production as in automobile manufacture, has been introduced. Recently, in perhaps the last 10 years, it has become possible to give warning and adapt to undesirable changes in operating conditions to develop what in effect is an intelligent welding system.

15.2 Metallurgical Developments

Up to the mid 1930s many of the steels used for constructional purposes were not readily weldable by the methods then available, largely owing to their carbon contents which produced cracking in hard welds and heat affected zones. The great exploitation of welding between the 1930s and 1945, and thereafter, led to the identification, explanation and rectification of the major problems which became apparent, concerned mainly with weld defects, cracking and microstructure. Early problems associated with slag entrapment, porosity, undercutting, etc. were remedied by modifications to electrode coatings which minimised slag entrapment and gave better deoxidation of the weld metal laid down by the predominant manual metal arc welding used, and by attention to the technique employed by the welder.

A major advance was the appreciation that much cracking was associated with the hardness of the martensite in the weld and HAZ, and by the low transformation temperature resulting in high transformation stresses and their inability to be relieved; hence the problems with the carbon contents then in use. Even the use of lower carbon contents, which began in the late 1930s, whilst helping, did not eliminate the cracking problem. Preheat and post-heat was introduced but this, whilst
being effective, made the welding process slower and less efficient. The advent of the concept of a ‘carbon equivalent’ (CE) below which it was possible to eliminate the use of welding preheat, was a significant advance. Many formulae for CE have been proposed for use in different situations such as weld heat input, thermal restraint severity and hydrogen content, in order to define the required preheat temperature or interpass temperature in multi-run welds (Cotton, 1976). Essentially, the CE formula is a measure of the effect of steel composition on $M_s$ hardenability and the hardness of martensite, and it was generally accepted that for freedom from weld metal and HAZ hydrogen induced cracking, a CE of $<0.41$ was required if preheat was to be avoided. Modern low carbon constructional steels fall readily within this criterion. Highly restrained welds or high hydrogen electrodes required lower values of CE and so drying of electrodes was important.

By virtue of their columnar grain solidification structure, weld metals can exhibit hot cracking along the line of intersection of the columnar grains. This produces a line of weakness to the solidification stresses and the cracking is exacerbated by the interdendritic segregation which produces low melting points in the segregated regions. Indices have been determined to predict whether a weld is prone to this type of cracking, which show that C, S, P and Nb are detrimental, whilst Si and Mn are not. Thus, a lower tendency for hot cracking required purer material, which applied to the base steel as well as the weld metal. Thus, the low C, S and P contents, together with the reduced residual/impurity contents produced by modern steelmaking practices, are beneficial. In austenitic stainless steels the effect of impurities can also be overcome by the presence of a few per cent of delta ferrite, which occurs in the interdendritic regions and dissolves the impurities, thus preventing low melting point segregates. Delta ferrite also helps to relieve solidification stresses. The control of the delta ferrite content is largely by composition and can be predicated from Schaeffler–Schneider diagrams. It is also advantageous to refine the weld metal grain size, which can be done using nitrogen and titanium additions to the weld metals, and this can be effective in both low alloy and certain stainless steels.

Very similar to hot cracking is intergranular liquidation cracking in the HAZ close to the weld bead, owing to the melting of certain phases along the austenite grain boundaries and the segregation of impurities at the austenite grain boundaries to produce a locally decreased melting point. Again equations have been developed showing how composition affects liquation cracking, and in this case they are applied to the base steel composition.

The role of S during welding has also been widely investigated. Two main problems have been encountered. The first is lamellar tearing which occurs in the base plate immediately below the HAZ and is a result of planar arrays of elongated inclusions, mainly MnS, which decrease the short transverse ductility. In T-joints particularly, such as are often produced in large engineering structures, the welding and contraction stresses cause through-thickness tensile stresses and cracking along the inclusion arrays. This problem was overcome in the 1970s by inclusion shape control, but it was an ephemeral technology, being superseded by the devel-
opment of cheap and efficient desulphurising steelmaking methods. However, and this shows the complex interactions that can occur, with very low MnS contents the steel was rendered more susceptible to hydrogen underbead cracking in the HAZ because MnS inclusions act as sinks for hydrogen and thus a reduced S content increased the cracking tendency. Lower hydrogen contents are now a requirement in these low sulphur steels in order to avoid this problem yet take full advantage of the freedom from lamellar tearing.

Another form of cracking that has been observed, particularly in certain low alloy creep resisting steels, is reheat cracking, which is intergranular in nature and occurs in the coarse grained region of the HAZ near to the weld metal when a weldment has been post-weld heat treated or has been in service for a considerable time at high temperature. Reheat cracking is often associated with the precipitation of MnS at the prior austenite grain boundaries after they have been taken into solution by the high HAZ temperatures. This is thus not dissimilar to overheating, but the cracking process itself is induced by creep during stress relief. It can be minimised by scavenging the S, or by replacing the MnS by more stable (less soluble) sulphides using Ti, Zr, Ca or rare earth additions, or in modern steels by the lower S content. Yet another form of intergranular cracking in the HAZ welds in both transformable and austenitic creep resisting steels is the so-called stress relief cracking. This is owing to the precipitation of carbides such as VC (in ferritic steels) and NbC or TiC (in austenitic steels) consequent on the solution of these carbides at high temperatures in the HAZ and their subsequent precipitation in the matrix by strain induced precipitation during stress relieving treatments. This strengthens the matrix, thereby throwing the strain onto the grain boundaries during stress relief and inducing grain boundary sliding and cavitation with a consequent intergranular fracture. It is thus a manifestation of low creep rupture ductility.

A problem associated with the welding of stainless steels from as long ago as the 1920s is the intergranular corrosion resulting from the precipitation of Cr23C6 in the austenite grain boundaries at the lower temperatures in the HAZ (weld decay). Conventionally, it has been minimised by stabilisation, using Ti or Nb additions which form sparingly soluble TiC and NbC and so lower the carbon in solution that a minimum of Cr23C6 can precipitate. This solution to the problem is not foolproof as at high temperatures in the HAZ some TiC or NbC can dissolve thereby allowing the kinetically favoured Cr23C6 to precipitate, especially during multipass welding. The most effective cure is to lower the carbon content of the steel to less than that at which Cr23C6 can precipitate, as is possible in the modern ultra-low carbon steels in which weld decay is not observed. A similar phenomenon can occur in the ferritic stainless steels when heated in the HAZ to above 900°C and in this case very low carbon steels are necessary to eliminate the problem owing to the very low solubility of carbides in the high chromium ferrite.

Since the 1950s much attention has been paid to: (a) grain size control in the HAZ and in the weld metal and (b) microstructural optimisation of the HAZ and the weld metal. Control of grain size, especially grain growth, is important in obtaining optimum properties in the weldment. It is possible now to refine considerably
the HAZ grain size even close to the weld metal by the use of well established grain refinement techniques involving second phase particles; TiN technology is a typical recent example. The importance of this method in transformable steels is that it causes the transformations to occur at higher temperatures, thereby producing less hard and less highly stressed microstructures which often have better toughness, especially when fine grained, and less susceptibility to hydrogen embrittlement effects.

Similar effects may also be produced in the ferritic and austenitic stainless steels which, in the absence of grain refining by second phase particles, can develop very coarse grains in the HAZ because the structures are often single phased. Control of the composition and constitution to allow the two-phase austenite and delta ferrite structure to exist over the whole range of HAZ temperatures materially prevents grain coarsening.

In the case of the microstructures produced, the major effect is in the transformable steels as typified by the HSLA constructional steels. Structures containing Widmanstätten ferrite or bainite can be deficient in toughness compared with the 'basket weave structure' of acicular ferrite. Studies of the detailed transformations occurring in the HAZ, and the lower carbon contents of current steels, have proved especially beneficial. Grain refinement is also beneficial, but it has been suggested that acicular ferrite is more beneficial than grain refinement (Dolby, 1982). Even more recently, in the 1990s, the introduction of inoculants into the steel to induce the acicular ferrite structure has been developed, first using TiN particles, but also by the use of titanium oxide compounds as sub-micrometre particles. The use of high titanium electrodes is well established to produce these types of oxide inclusions in the fusion zone. No doubt further work on the microstructural control of both the HAZ and weld metal will continue in the twenty-first century.

Work is also going on to control the two-phase structure, which can be developed in ferritic stainless steels when austenite precipitates in a Widmanstätten form from a single phase ferrite at high HAZ temperatures and in the weld metal. This austenite often transforms to martensite with detrimental effects on toughness. Work will doubtless continue to establish precisely how control of base metal and weld metal affects the constitution, in order to produce improved properties.

15.3 Concluding Remarks

It can be seen that at the end of the twentieth century, it is probably fair to comment, that virtually all types of steel could be effectively welded if attention is paid to the welding process and the conditions of heating, solidification and cooling. The understanding of welding metallurgy is now very comprehensive (Easterling, 1983) and it is possible to eliminate or minimise many of the common weld defects and cracking problems that are encountered. However, a cautionary note should be struck because, especially in weldments of creep resisting steels in components, which have now been operating for very long times at high temperatures, new and apparently unexplained cracking effects have been observed. These may turn out
to be manifestations of known phenomena, but their investigation will probably form a subject for study for many years to come.

A problem of concern to the fabricator in the 1980s was that of weld penetration. With the introduction of the new ultra-pure steels, the shape of the weld pool could change significantly to give a wider, shallower pool, compared with that in steels of lower purity. This has been shown to be a result of Marangoni convection, which is associated with the temperature dependence of surface energy and the associated effects of surface active impurities, such as S. This controls the direction of flow in the liquid pool. Methods of controlling the surface active impurity levels have been proposed as these can change the welding speed by a factor of three or more to give the same penetration. Such studies may well continue in the twenty-first century.

16. SURFACE ENGINEERING IN THE TWENTIETH CENTURY

There are certain applications for steel where the surface properties are extremely important. These applications usually involve corrosion resistance and/or wear, and the type of treatment of the surface is dependent upon which of these two effects are important.

16.1 Corrosion Resistance

The most extensively used coating processes, i.e. tin-plating and galvanising have been described, the type of coating being dependent on the nature and severity of the corroding medium. The galvanised components or sheets are suited to atmospheric and aqueous corrosion, whilst tinplate is capable of resisting attack by fruit juices and foodstuffs. Since 1900 a variety of coatings and methods of application have been introduced, catering for a wide range of components and corrosive environments.

Apart from the hot dip process, which is used for Terne metal and aluminium as well as for zinc and tin, one of the earliest methods of coating steel was by a (metal) cementation process. Steel components were placed in a rotating container with a powder of the required metal coating and heated to a suitable temperature. Probably the best known of these processes is Sherardising, introduced about 1900, used for applying a zinc coating. Similar processes are used for chromising, aluminising (1925–1930) and siliconising. In the case of siliconising the silicon rich layer, up to 2 mm thick, is very hard, and is resistant to non-oxidising acids. It is also resistant to oxidation up to about 850°C. Aluminised surfaces are used to protect against oxidation at elevated temperatures, e.g. in pyrometer tubes and superheater tubes.

Metal spraying was first introduced around 1910. The coating metal, in wire form, was fed into an air-gas flame, where it melted, and was projected by the gas velocity onto the workpiece. A modern development of this process in the 1980s is
that of spray casting, involving gas or steam atomising of a liquid metal stream. Following the flame-gun process, the liquid or hot powder particles may be projected by electric arc spraying, high octane fuel spraying (whether continuous or by intermittent explosion) or more recently plasma spraying. The latter has been used for the deposition of higher melting point materials such as metal oxides. Low pressure plasma spraying and inert atmosphere plasma spraying have been used in the deposition of oxidation resistant coatings for gas turbine engine components.

Cladding processes have been used to give surface characteristics of the cladding metal applied to a steel base. Copper and aluminium have been applied to steel by either casting these elements around a steel plate or rod, or by hot rolling sandwiches of these materials. In the latter half of the twentieth century, stainless cladding has been applied to low carbon steel plates or rods. In the case of rods, low carbon steel bars have been inserted into a close fitting stainless steel tube, and the aggregate bar then hot rolled. Composite plates with stainless steel surfaces have been produced by hot rolling, the initial sandwich being either edge welded or explosively bonded. Cladding cannot be simply regarded as a surface engineering process, as the bulk properties of the steel substrate are less important to the component product than is the relatively low cost of the low carbon steel filling.

Weld deposition has also developed since the 1960s, as for example in the deposition of high chromium irons on the surface of rolling mill rolls. This application is practised mainly as a wear replacement (or build-up) method, and the coating was selected more for its hardness and wear resistance than for its corrosion resistance.

Two other types of corrosion resistant coating have maintained significant markets for steel. The first of these was the enamelling of steel sheet so commonly seen in white-ware products, i.e. refrigerators, cookers etc. The enamelling process is a matter for the component producer but the question of good adherence between the enamel and the steel obviously requires close collaboration between the steel producer and the component manufacturer. Traditionally the steel was cleaned and a ground coat (or slip) of enamel ingredients applied. The strip may have been dipped in a nickel solution to improve the coating adherence. The ground coat often may be dark blue owing to the cobalt oxide commonly used. Finish coats are applied when a light colour or additional protection is required. Much experimental work has been directed at single finish coats for obvious economic reasons, and very low carbon steels with controlled grain size have proved suitable for this process.

The second type of coating is the organic coating on strip. Traditional roofing and sheeting was of galvanised steel. Alternatively, uncoated steel could be painted and there is a considerable body of information on surface preparation, undercoats and paint types available both from paint specialists and from steel suppliers. However, painting and maintenance are costly, and galvanised surfaces (which may be bonderised for subsequent painting) lack aesthetic appeal for the modern architect. In the 1980s the steel strip producers developed modern continuous lines for organic coatings in much the same way that continuous hot dipping or electrolytic lines were used for tinplate and galvanised strip. The types and range of
coatings are extremely complex, and the coating lines may comprise cleaning, undercoating, drying, coating and curing processes, the curing processes being effected in infra-red, electric, or more recently UV furnaces at temperatures up to 200°C. Such cured or baked coatings are extremely durable and will even allow limited cold forming operations.

16.2 Surface Hardening

The surface hardening treatments available at the start of the century were basically flame hardening and carburising. The first is a purely thermal treatment where the surface is austenitised and then quenched to give a martensitic structure, usually accompanied by the development of compressive surface stresses. The second, carburising, involves a change in chemistry, i.e. an increase in carbon content, followed by a suitable heat treatment, the harder surface resulting from the increased carbon content. The hard surfaces are required to resist wear and abrasion, whilst the bulk properties are essentially those of the core material; this is particularly true for toughness where the core must have a certain strength and toughness level. Early problems with carburising were associated with abnormal cementite distribution and with distortion arising either during carburising at 900°C or heat treatment, which invariably involved reaustenitising at high temperatures to harden the low carbon core.

The basic principle of flame hardening has remained unchanged through the present century, but the methods of heating have changed quite dramatically. Induction heating had been introduced by 1950 and subsequently high frequency resistance heating was introduced in the 1980s, both of these processes being more controllable than flame heating.

In the 1970s the development of expertise with electron beams and their control led to a consideration of their use for surface hardening. A focused electron beam could be scanned across a surface and was found to give exactly the same effects as were produced by flame hardening, except that the extremely fine spot gave a very shallow hardened depth. The rapid cooling to produce a martensitic structure was provided by the bulk of the steel in relation to the small heated region. Electromagnetic control of the beam also allowed a patterned raster to be hardened. A major disadvantage was the necessity of a high vacuum chamber for the electron beam to operate. In the 1980s, coincident with the development of lasers for cutting and welding, laser surface hardening was explored and proved to be highly successful from a practicability standpoint. The economic case for these processes remains to be proved.

Surface hardening by chemical change has undergone more dramatic changes. In the 1920s nitriding was introduced. Nitrogen shows a greater solubility in the ferrite phase, has a lower eutectoid temperature and diffuses slightly more rapidly than does carbon. In general, nitriding produces a harder surface but over a shallower depth. The properties make nitriding a preferred option for abrasion resistance under conditions of light loading. With heavy loading, carburised components are
still preferred, so that case hardening by carburising still retains a dominant position over other methods of case hardening, even though there are substantial outlets for parts which are case hardened by other processes. One of the factors favouring the nitriding process is the reduced distortion. Because nitriding is often carried out at about 570°C, the thermal differential stresses are reduced and also the nitriding takes place in the ferrite temperature range, thus eliminating transformation stresses. The early process of nitriding (or carbo-nitriding) in molten cyanide baths has been discontinued for environmental and safety reasons. Gaseous nitriding using a mixture of ammonia and hydrogen is more controllable, as the nitrogen partial pressure can be changed by changing the hydrogen content of the gas mixture.

Plasma nitriding was first developed by Bernard Berghams in the 1930s, but only gained worldwide popularity in the 1980s. In this method, applying a voltage of 700–1000 V from the container or the workpiece through a low pressure (a few millibars) atmosphere of hydrogen and nitrogen, containing between 5 and 50% nitrogen, provides a uniform and stable plasma. The charged nitrogen ions collide with the cathodic workpiece and are absorbed. The plasma nitriding process is conducted at a temperature of between 400 and 565°C.

Nitro-carburising was introduced as a molten salt bath treatment in 1947, and involved the use of alkali metal cyanides and cyanates. The process was further developed to avoid the use of these highly toxic compounds and various proprietary methods became available in the late 1970s including Tufftriding (Germany) the Oxynit Process (UK) and the Nitrotec Process (Lucas Industries). All these processes involve a nitriding stage resulting in the formation of a hexagonal nitride at the surface, which is then followed by a second stage, resulting in surface oxidation. The resulting surfaces are not only very hard, but also show a degree of corrosion resistance.

Many other surface hardening processes have been applied in the last 20–30 years, e.g. boronising, carbide diffusion, gas carbo-nitriding, plasma carburising, vacuum carburising, ion implantation and many others. Their relevance to bulk steel production is not high in tonnage terms, but the successful application of these processes has kept open another market for steel. Equally, the use of physical vapour deposition and chemical vapour deposition methods to increase the hardness and wear resistance of tools, knives, etc. has also helped to preserve a further market for steel products.

17. THE DEVELOPMENT OF INVESTIGATIONAL TECHNIQUES IN THE TWENTIETH CENTURY

It is sometimes maintained that the unprecedented rise in steel production, particularly in the second half of the twentieth century, has been the result almost exclusively of improved and more efficient steelmaking and processing methods coupled with computer control. This is not the whole story. There was also a demand for improved properties and especially combinations of properties along
with greater consistency, in order to sell the increased amounts of steel. If the improved properties had not been forthcoming, no amount of improved steelmaking and production methods would have sufficed to make a return on the capital costs involved, as demand would have been insufficient.

The properties of steels are, however, dependent on the microstructure, and in the early years of the twentieth century, in fact up to the 1950s, the microstructure could only be revealed by optical microscopy. The use of X-ray diffraction from the 1920s onwards meant that it was possible to identify generally the phases present in steels, but it was not possible to uniquely identify particular particles present in the structure. Also X-ray diffraction techniques were by no means routine and could give no indication of the spatial distribution of the phases identified, i.e. the microstructure.

Another important result of technique developments is the discovery of new facts on which conceptual innovations are based. Thus the advent of new techniques leads to a greater depth of understanding. The outcome of techniques and conceptual innovations is that the subject moves further into the realm of science so that new and improved steels can be produced based on sound science, and the processing practices can be more securely optimised. In fact one can throughout much of the twentieth century trace the successive stages of technique development followed by conceptual development, at least up to the 1970s. Interestingly, and disappointingly, the last twenty years have been largely devoid of conceptual developments. Possible reasons for this have been that, since about 1980, there has been not so much new technique development but rather the refinement of existing techniques and their computer control. Hence new and hitherto unknown facts have rarely been uncovered to form the basis for conceptual innovation. Ever increasing masses of data do not necessarily replace original thought and may even hinder conceptual understanding. Equally, uncritical use of computer modelling can be inimical to innovative thinking and experimentation.

17.1 Optical Metallography

As has already been stated, the standard of the best optical metallography was high at the beginning of the century, bearing in mind the types of microscope, lenses and projection equipment available. Up to the 1920s, optical bench attachments were used for photomicroscopy, with all their inherent mechanical instability. Equally, the stability and evenness of illumination was poor. Only in the 1930s was integral projection built into microscopes. The advantages of critical illumination and oil immersion lenses was appreciated early in the century. Abbey (1848) and Rayleigh had much earlier established the theory of image formation and that the resolution of the microscope was given by

$$\delta = \frac{k\lambda}{(NA)}$$

where \(\delta\) is the resolution, \(\lambda\) the wavelength of the illumination, (NA) the numerical
aperture of the lens system, and $k$ a constant ($0.5$ for line objects). The largest numerical aperture, using oil immersion, is $\sim 1.3$ so that the resolution is of the order of about $0.4$ of the wavelength of the light used.

This limits the detail which can be resolved, but even as late as 1926 the implications of this in terms of the maximum useful magnification were apparently not fully appreciated. This magnification, which just increases the distance between resolved images to that which can be seen to be resolved by the human eye, is of the order of $\times 1000$. Any larger magnification simply enlarges an unresolved image, yet Sauveur (1926) recommended magnifications up to 5000! Resolution is not the same as perception, however, which depends on intensity or colour contrast. Features can be perceived, that are much smaller ($1/10$ to $1/100$) than the resolution without being resolved. Techniques such as dark field, oblique and opaque stop microscopy were readily available by the 1920s to improve perception.

Another limiting feature of optical microscopy in the early decades of the twentieth century was the method of specimen preparation. Grinding on SiC papers and polishing using alumina or chromic oxide was manual and could lead to many artefacts. Also, SiC particles could be embedded in the surface and not infrequently were thought to be non-metallic inclusions. The production of uniform particle sized polishing media was not easy as the size of such particles was established by levigation which was a lengthy operation. It was only in the 1930s that commercially produced alumina polishing suspensions became available. Many and varied etching reagents were investigated during the period up to, and indeed after, 1930, some producing spectacular artefacts. Often, stain etching was used to differentiate between phases, sometimes with most photogenic results as in the case of the phosphide eutectic in cast irons. Heat tinting was developed rather early (1900) to distinguish different phases by the interference colours caused by the oxide films produced on them, but thermal etching was developed much later when vacuum equipment became readily available, although being first used in 1890 by Osmond. Non-metallic inclusions could cause major polishing problems as the harder inclusions, e.g. $\text{Al}_2\text{O}_3$, were pitted-out and dragged across the specimen surface, producing severe distortion.

Gradually, however, many of the problems were recognised and overcome with the introduction of automatic polishing machines, vibratory polishers and the availability of highly size-controlled diamond pastes in the 1950s. In an attempt to overcome problems with mechanical methods, electrolytic polishing was developed by Jacquet in 1930, and chemical polishing was developed later, after 1945. Electrolytic etching, so necessary for stainless steels, was systematically studied by Adcock in 1921, and the widely used oxalic acid electrolytic etch came into use after 1936. Despite these developments, it is probable that the structure of graphite in cast irons was never properly revealed until the work of Morrogh (BCIRA) in the late 1940s.

Many attempts were made up to about 1950 to improve the resolution of optical microscopy using such techniques as interferometry, which could give a height resolution of $15-20$ Å, but was still limited in terms of lateral resolution. Even the use
of ultra-violet wavelengths were investigated but suffered from the need to have special imaging facilities, quartz glass lenses and special photographic plates. These and other techniques to improve the resolution of optical microscopes were, however, overtaken in the early 1950s by the development of reliable electron microscopes with potential resolutions down to 1 Å, i.e. three orders of magnitude better than the optical instrument.

Polarised light was never widely used in the general metallography of steels because of their isotropic nature, but one use involved the examination of etched surfaces, the varying facetting resulting from the orientation differences between grains causing different degrees of elliptical polarisation and thereby revealing orientation effects. Other limited applications involved the production of anisotropic epitaxial films on selected phases by stain etching which, together with the presence of pores or furrowing of the stain film, could reveal the phases under polarised light. Perhaps the main use of polarised light in ferrous metallography was in the examination of non-metallic inclusions, many of the crystalline non-metallic phases being anisotropic. In addition there was preferential absorption of certain wavelengths, leading to colour effects which were reputed to be an identification tool. It was also observed that the glassy silicate inclusions exhibited specific colours under polarised light, which were really transmission colours but which were believed to be a method for identification. This was not actually true. During the period up to about 1955, a comprehensive scheme for identifying inclusions by polarised light was built up, but this was far from accurate and led to many identification errors. The use of polarised light for this purpose, and indeed the use of various etching reagents to identify inclusions, was brought to an abrupt end by the development of microprobe analysis, which technique spread rapidly from about 1957 and which allowed the chemical composition of individual inclusions to be determined.

Other techniques of limited use in general ferrous metallography include micro-radiography which had its origins in the work of Heycock and Neville in 1898, but which was used more in 1930–1960 and could give information on both composition and structure albeit at very limited resolutions. High temperature microscopy also found limited use, but since the 1960s has largely been disregarded. Nevertheless useful work was done on shear transformations and liquation effects.

17.2 Quantitative Metallography

The genesis of quantitative metallography lies in the fields of geology and petrology, some 150 years ago. The fundamental relationships describing a microstructure were defined in the nineteenth century by Delesse (1848), Sorby (1856) and Rosival (1903), whilst in 1931 Scheil carried out his classical work on particle size distribution in multiphase aggregates. It is only in the last 40–50 years that a detailed study has been made of the reproducibility of the techniques and the errors involved.
For much of the twentieth century a semi-quantitative description of microstructure was employed for process control. For at least eighty years grain size was measured by comparison with standard charts. The ASTM grain size chart is such a method. Equally the non-metallic inclusion content of a steel was for some seventy years matched to standard charts of arbitrary inclusion content and size-distribution. Similar charts were used for carbides in tool steels.

These methods were all very subjective, but from the 1940s onwards increasing attempts were made to relate the microstructure quantitatively to the properties. It was soon apparent that much more reliable and quantitative descriptions of the microstructure were necessary and quantitative metallography developed very rapidly. At first manual methods were used to determine volume fraction by point counting or lineal analysis. The measurements were tedious and labour intensive, but the errors associated with such measurements were quantified by the late 1960s. Many other measurements were made, such as grain size even in duplex structures and the size distribution of particles (1931), both of which have been essential for experimental determinations of nucleation and growth phenomena. Interfacial angle measurements were made for interface or grain boundary energies, together with grain boundary or interphase surface areas. With the advent of electron microscopy the techniques have been extended to replicas and thin foils.

Perhaps the greatest advance occurred with the development of instruments capable of automatically measuring and recording many stereological parameters, the first being the flying spot microscope in 1952, which was rapidly applied to the time-consuming process of inclusion counting. This quickly developed into the quantitative television microscope and eventually, in the last twenty years, into a fully automated instrument, the image analyser. Unfortunately successive models were not always compatible and to keep abreast of developments was expensive.

Many stereological parameters were able to be measured and the rapid production of voluminous computer data was often disconcerting. Nevertheless the technique did render unnecessary the many manual inclusion counting technicians working on quality control in works metallographic laboratories and supplanted very subjective data, individual operators varying greatly and not always being self-consistent. As so often happens, events overtook this method of inclusion counting in that developments in steelmaking practices produced such low O₂ and S contents that, to obtain representative data, very large areas had to be scanned. Moreover it was not possible to distinguish positively between different types of inclusion, except by using a contrast effect which was often less than satisfactory.

Attempts were then made to develop an electron beam scanning technique and to produce images from characteristic X-ray emission for different elements present in the inclusions. This highly sophisticated technique never reached commercial production. The problem of inclusion counting thus became a statistical one and was better addressed by refinements in the chemical techniques which gave bulk O₂ and S contents. Image analysers however continued to develop and are now commonplace for normal routine metallographic work, but many inclusion standards still refer to various comparative chart systems.
17.3 Electron Optical Techniques

Once it was realised that electrons could be focused by electro-magnetic fields and that electrons could be diffracted by crystals, the potential for an electron microscope was apparent. As shown previously, the resolution is directly proportional to the wavelength and inversely proportional to the numerical aperture. Hence, whilst optical microscopes had a resolution of some 2000 Å, electron microscopes operating at 100 kV would have a resolution of 8 Å or better. By careful attention to the design of the lens systems, stability of the power supply and alignment of the instrument, together with increases in the accelerating voltage up to 1 MV, theoretical resolutions of the order of 1 Å were possible.

The electron microscope was first developed in 1931 and by 1939 had been applied to biology. The first electron microscope used by the steel industry in the UK was supplied in the 1940s under Lease-Lend, to a laboratory in Sheffield. Unfortunately it was unsatisfactory, which is not surprising as the first few generations of electron microscope were notoriously user-unfriendly. The major applications to steel, however, occurred after the mid 1950s and tremendous advances have been made to render modern microscopes user-friendly. The illumination mode, or diffraction, can be obtained by the press of a switch and a mouse controls specimen movement with no mechanical backlash. With the use of X-ray analytical attachments, the chemical analysis of a particle or very small region can be obtained readily.

In the early days the electron microscopes were transmission instruments and the major advances were initially in specimen preparation techniques. Starting with plastic and then carbon replicas, extraction replicas were rapidly developed by the mid 1950s, which enabled individual particles to be examined and identified by electron diffraction. This was followed by the use of thin metallic films which were rapidly developed and used by the late 1950s and led to the direct verification of many features which had been theoretically predicted, e.g. dislocations, G–P zones and associated strain fields, vacancy clusters, stacking faults and the resolution of crystal lattices. The need to obtain transmission through thicker films, to eliminate surface controlled phenomena and allow dynamic experiments to be carried out in situ in the microscope, together with other advantages (not to mention potentially increased resolution) led to the use of increased accelerating voltages up to 1 MV in the 1960s. Most of the arguments for the development of the 1 MV microscope, and very few were actually manufactured, proved optimistic. It may be questioned what was achieved at huge cost using the 1 MV microscope, which could not have been achieved using a 100–200 kV microscope. Possibly the study of the structure of mineralogical and geological specimens is one of them and extension of this work to refractory materials and slag attack was an unexploited opportunity. It is instructive that no 1 MV microscopes are currently in operation owing to the development of high intensity LaB₆ and field emission guns, together with scanning transmission techniques that have enabled the advantages of 1 MV microscopes to be realised with only 300–400 kV, which can be also more readily adapted to the use of X-ray dispersive and non-dispersive analysis.
During the 1950s the development of the electron probe microanalyser enabled characteristic X-rays to be generated by the bombardment of a small area of a specimen using a scanning focused beam of electrons. With subsequent wavelength or energy discrimination it was possible to obtain the chemical analysis with a resolution of the order of 1 μm.

Another interesting development in the 1970s was the high resolution electron microscope which could resolve metal crystal structures, although the images obtained required computer aided interpretation. Many other specialised electron optical techniques were also developed from 1950 onwards, including convergent beam electron diffraction, various field emission microscopes using different stimulating radiations, low energy electron diffraction to examine the atomic structure of surfaces, and field ion microscopy in which individual atoms can be resolved under very specific specimen configurations.

Various methods for examining segregation at surfaces, grain boundaries and phase interfaces were also developed, such as Auger electron spectroscopy and electron spectroscopy for chemical analysis using X-rays to excite both Auger electrons and photo electrons. Both techniques could give chemical analysis data from surface atoms up to 5–20 atoms deep and information about the nature of bonding of surface atoms. Sputtering could then be used to provide depth profiling. In the 1960s secondary ion mass spectrometry was developed in which the surface to be examined is bombarded by positive ions, and the sputtered ions are collected and analysed by a mass spectrometer so that it is also possible to image the surface with the analysed ions. Thus, the distribution of each atomic component can be displayed in the image. Finally and most recently in the last two decades, the atom probe has been designed which combines field ion microscopy with mass spectrometry and sputtering to allow actual atoms in the lattice to be identified. At the end of the twentieth century this seems to be the ultimate technique for chemical analysis on an atomic scale.

Many of the above techniques were predominantly confined to specialised research laboratories and did not find their way into the routine works metallographic laboratory. The same cannot be said for the scanning electron microscope, developed in the mid 1950s and improved continually since then. It is much more user-friendly, requiring a minimum of specimen preparation and having the ability to use quite large specimens, although not giving the resolution of the transmission electron microscope. Coupled with ever smaller focused electron beams and with ever more sophisticated X-ray analytical facilities, this instrument has proved a real boon to the metallurgist. It quickly rendered obsolete the simple electron probe microanalyser. It has now become commonplace in many routine laboratories and has arguably been the most significant and widely used technique of the last forty years.

17.4 Chemical Analysis

Revolutionary advances were made in the twentieth century. Even at the start of the 1950s the majority of chemical analysis was by wet methods, which were time
consuming, and the results of which could not be fed back sufficiently rapidly to control the steelmaking process. Hence the prerequisites for steelmaking improvements in terms of output were not then available. Developments in colourimetric and absorptiometric methods occurred but these did not really address the major problem of the slowness of the methods. Prior to 1940, vacuum fusion techniques for the analysis of gases in steel were a distinct advance and the temperature dependence of, for example, the breakdown of the different oxides could be used to establish the relative amounts of alumina, silicon based and iron based oxides. The development in this period of the aluminium grain refined steels led to the development of extraction techniques for the determination of nitrogen as AlN, the ester-halogen method, which enabled not only the nitrogen combined as AlN to be established, but also the 'free nitrogen' present in the steel. With the development of the microalloyed steels after 1950, this technique was further developed to enable the nitrogen combined as the more stable nitrides such as NbN, VN, TiN, ZrN to be determined.

Although by 1950 spectrographic analysis had been developed, it was not generally available in the routine chemical laboratory. The instrumental developments capable of allowing many elements to be determined, first consecutively and then concurrently, rapidly followed and were introduced into steelworks laboratories which, with the rapid processing of the results and their ability to be transmitted to the steelmakers, set the scene for the control of steelmaking by virtually real-time analysis and hence for the tremendous developments in steelmaking practice. This was further enhanced by the use of X-ray fluorescence analysis from the 1960s onwards. Since then many novel types of physical process have been used for the determination of chemical analysis culminating in the last 10–15 years in the use of instruments employing solid state electrolytes in the steelmaking vessel for the measurement of oxygen. This has contributed to the rapidity of the control of steelmaking, the development of deoxidation and desulphurisation methods and the ability to reproducibly achieve very low O₂ (5ppm) and S (7ppm) contents, and the manufacture of steels so free from non-metallic inclusions as to be inconceivable in the first seventy-five years of the century. The demise of wet chemical methods was assured and rapid.

This leads on to a brief description of the analysis of non-metallic inclusions. Up to the 1950s, the identification of non-metallic inclusions had been solely by optical metallography; many misidentifications were made, and possibly the last comprehensive account of such techniques was published in 1962. This followed on the first definitive work on the subject by Benedicks and Lofquist in 1930, although previous schemes for inclusion identification had been published by Wohrman (1928) and Campbell and Comstock (1923). None of these techniques could provide the analyses of the inclusions, although X-ray studies of extracted inclusions enabled the crystalline phases to be identified. These limitations prohibited the origins of the inclusions to be definitively established, with a consequent inability to identify uniquely their origins during steelmaking. Consequently, in the 1950s and early 1960s very considerable efforts were made to extract the inclusions by chemical or
electrolytic methods (Klinger-Koch, 1949), analyse the chemical composition of the extract and identify the crystalline phases by X-ray diffraction. The labour and expense was immense and only related to the sum of all the inclusions in the extract and not to specific types. As so often happens, the development of new techniques overtook events, and the advent of the X-ray microprobe analyser in the 1960s rendered all previous methods obsolete. This resulted in the definitive works of Kiessling and Lange in the 1960s and 1970s. An even further advance was made when scanning electron microscopes were fitted with X-ray analytical facilities. Coupled with the technique of deep etching, inclusions can now be revealed in three dimensions, the chemical analysis of all the phases, crystalline and non-crystalline, can be determined and the deformation and fracture of inclusions can be studied in detail. This has had a great influence on the knowledge of the origin and constitution of inclusions and their influence on properties, and has contributed materially to the development of modern steelmaking practices.

17.5 Other Physical Techniques

During 1900-1949 much progress was made in developing dilatometric, thermal analysis, specific heat, electrical resistance and magnetic techniques for the study of metals and alloys. These were all applied to steels, but they tended to be confined to research laboratories and were not readily used in routine works laboratories. These will not be described in detail; suffice it to say that several areas of significance were developed. The first was the theoretical analysis which enabled the results to be used quantitatively. Next was the continuous measurement of the property with change of temperature, and the ability to develop methods for rapidly heating or cooling the specimen. Then followed the automatic recording of the results and finally the use of computer techniques to enable a direct print-out and storage of the derived data from the raw physical measurements after about 1970. More recently equipment has been developed which enables complex thermo-mechanical deformation cycles to be applied to a small specimen, which can then be cooled at various rates and the transformations studied dilatometrically. It must be appreciated, however, that these techniques gave no indication of microstructural changes, which relied heavily on the use of the high resolution electron metallography, concurrently being developed.

Although mention has been made previously of X-ray diffraction, it must be appreciated that X-rays had only been discovered in 1895 (Rontgen) and it was not until 1912 that Laue suggested that X-rays could be diffracted by crystal lattices. In a very short time, practical evidence of this was established by Bragg (1913), which led to the Bragg Law. The application of X-rays to crystallographic structure was then rapid. The powder (1917) and back reflection (1928) methods were most widely applied to steels. Focusing cameras were developed (1919) as also were monochromators (1933). The most important instrumental development to produce a very efficient laboratory apparatus was that of the diffractometer, using a movable X-ray detector which electronically measured the intensity of the dif-
fracted X-rays as a function of the diffraction angle. This led, more recently, to computerised interpretation to give rapid and positive identification of the phases present. The ability of X-ray diffraction techniques to determine crystallographic orientation, and its potential for determining preferred orientation effects in polycrystalline materials, has been known since 1924, and the use of stereographic projections and pole figure to present the data has played a large part in the development of high formability (deep drawing) steels, using texture goniometers and automatic recording in recent years.

Mention must be made of the use of damping capacity measurements and internal friction effects. The effects were known from the 1940s but were only applied effectively to steels in 1959/1960. Two major effects have been studied, namely the Snoek effect (1941) to the diffusion of interstitial atoms in the bcc alpha iron lattice and the Koster effect (1954) resulting from interstitial atom-dislocation interactions. The interpretation of the internal friction peaks can be very complex, and widespread use of the technique has not taken place. However, a very high frequency internal friction technique was used in the 1960s to provide data on the occurrence of hydrogen in the ferrite lattice and its association with hairline cracking and delayed failure. Finally it is probably relevant to mention the use of Mossbauer spectroscopy which, as with Auger and electron spectroscopy for chemical analysis, can give information on atom bonding effects.

17.6 Mechanical Testing

Hardness testing has hardly altered over the years, the Brinell test having been developed in 1900 followed by the use of conical or pyramidal indentors and the Meyer analysis in 1908. The Shore Scleroscope rebound tester was developed in 1918 and was still in use in the 1960s and later. The Rockwell test was introduced in 1922 and the Vickers test in 1925. The Knoop semi-microhardness instrument was operative by 1939, whilst microhardness attachments were available for many projection microscopes after 1950, allowing the hardness of individual phases in the microstructure to be determined.

In essence the tensile test has not changed dramatically over the years. Engineering improvements to the design of tensile machines resulted, particularly after about 1945, in much more compact machines employing hydraulic rather than mechanical principles, the use of variable strain rates and the introduction of so-called ‘hard’ machines capable of following the discontinuous yielding phenomenon. Later still the use of dial gauges and optical extensometers was superseded by transducer strain gauges and load cells. These paved the way for the complete computerisation of the testing procedure in the last twenty or thirty years. In addition it became commonplace to have ancillary equipment which enabled the tensile test to be carried out over a very wide range of temperatures and also ‘in vacuum’ or in selected environments.

Formability of materials had long been assessed by bend testing of plate and sheet and by torsion testing of wire materials. The rise of the sheet steel market for
automobile bodies and 'white' products in 1910–1930 resulted in the development of specialised tests for the evaluation of deep drawing and stretch forming behaviour, which rapidly became standardised and enabled the strain ratio ($r$) to be measured to assess anisotropy and textural effects. Cupping and bulge tests became commonplace in both sheet steel producer and user laboratories. The use of modelling techniques and finite element analysis has been a feature of the last two or three decades.

Brittle fracture had been documented as early as 1886 and the general idea of the fracture transition had been postulated. In fact ductile–brittle transition curves, using various techniques, were being established in the early 1930s. The notched bar impact test, Charpy and Izod, had been conceived early in the twentieth century to assess the ability of materials to resist fracture under very rapid strain or impact conditions and were well established by the early 1920s. The form of the notch was not standardised until much later, together with specimen dimensions, culminating after the 1950s in the current widely used V-notched Charpy test. It was appreciated, however, that tests on small specimens did not always indicate the behaviour of large sections and a multiplicity of fracture tests were developed in the 1940s and 1950s consequent upon the brittle fracture observed in ship plate and other large engineering structures. Some of these tests used complex notch or even weld configurations, and enormous testing machines were built which could test full size plates. The main drawback to notch bar impact testing was that it could give no indication of the allowable defect size, and so fracture toughness testing was conceived in the 1950s.

The original ideas were due to Griffiths (1921) and were developed by Irwin and other workers in the 1950s. Many complex tests methods were used. It required some time to appreciate that fracture toughness parameters such as $K_{IC}$ were not unique material parameters, but were very dependent on the microstructure of the test specimen and the fracture mechanism involved. Fracture toughness measurements are of great relevance to engineering design, to the prediction of critical defect sizes and also to defining the defect monitoring procedures for large scale structures. In the 1970s fracture toughness testing was extended to study environmentally controlled fracture as in stress corrosion, and fracture by creep and fatigue. This led to the development of tests to measure the progressive growth of subcritical cracks under stress corrosion, creep and fatigue conditions until critical crack sizes were exceeded. Thus the effective service life of a structure could be predicted. Despite the obvious advantages of fracture toughness testing, it is time consuming and expensive. Consequently it is not surprising that the Charpy test is still very widely used as a quality control tool, despite many predictions of its demise.

Fatigue failures under alternating stress have been recognised since 1850 and during the twentieth century there has been a progressive development of fatigue testing techniques which were listed by the ASTM in 1949. These included rotational bending (Wohler), planar bending and push–pull techniques. The usual process of instrumental developments took place to enable more efficient testing and presentation of data. The effect of stress concentrations were studied by means
of notched fatigue tests from the 1940s onwards and the techniques for applying superimposed stresses and combined stresses were developed. In addition the analysis of fatigue data by Goodman, Goldberg and Soderberg methods enabled the effects of mean stress to be studied and more latterly fracture toughness techniques have been used to study fatigue crack growth. Statistical approaches to the analysis of fatigue data were also applied. After the development of gas turbines and other high temperature engines, the effects of temperature on the fatigue properties were studied, which then resulted in the measurement of creep-fatigue properties (1980s). The appreciation that size effects were also apparent caused, in the 1950s and 1960s, the building of large equipment to assess the fatigue properties, sometimes of full-scale engineering structures. More specialised techniques that were developed included thermal, fretting and corrosion fatigue and the simulation of actual service conditions as in the study of roller bearing fatigue (1950/1960).

The phenomenon of creep was first established by Andrade (1914), but the machines for creep testing were not available for routine laboratory use until the development of creep resisting steels in the 1920s and 1930s for electrical power generation. A further stimulus to creep testing occurred after the development of gas turbine aero engines (from the mid 1940s) when large creep testing laboratories were installed by many steelmakers and research organisations. The initial equipment involved short time low sensitivity tests using dial gauge extensometers and the longer time high sensitivity tests using optical level extensometers. With increasing life requirements, sophistication of the temperature control equipment developed for tests lasting many tens of thousands of hours. The great need for increased numbers of test points was met by the use of several specimens in a strand and up to four strands in one furnace, each specimen being fitted with its own extensometer. The increased complexity of such equipment and the problem of temperature control and the failure (or extraction) of one specimen in a strand were appreciable. Eventually, in the 1960s and 1970s, improvements in instrumentation by strain gauges, load cells and computer control, with central monitoring stations were introduced.

Mention must be made also of the development of stress relaxation testing for bolting applications, which were manpower intensive, particularly in the initial rapid primary creep stage. Again instrumentation and feedback control helped to ease the problems. A huge amount of creep and rupture data were accumulated on the many creep resisting steels which were developed, which eventually were summarised in national publications by many countries.

Many other tests, some of which had limited application, were also developed, such as stress corrosion tests and hot workability tests using torsion or rapid tensile techniques. Although not really mechanical tests, the many types of machinability tests may also be mentioned but space prevents the discussion of their development.

17.7 Conclusions

It can be seen that during the twentieth century there has been a eruption of technique developments which probably reached its zenith in the period 1950–1980. At
the end of the twentieth century, the metallurgist has at his disposal a formidable armoury of sophisticated techniques with which to study the nature of metals, and steels in particular. The development of these methods of investigation occupied an inordinate time and effort and was very expensive. Was this partially responsible for the lack of conceptual innovation, which has been apparent since about 1980? It is now possible to accumulate data so easily that it becomes an end in itself. Much of the data may be superfluous and possibly the twenty-first century will see this general position reversed with beneficial effects.

Finally, mention must be made of the use of physical and mathematical modelling techniques, which have become such a feature of modern research methodology. These are too many to itemise but have the ability to use ever cheaper computer power to model processes and phenomena in order to make predictions which can be validated against existing observations. The methods are much more convenient and less expensive than the time consuming experimental approach, but, effective as the human intellect is, it can lead to mistakes which initiate a completely wrong line of thought. Perhaps the greatest benefit of modelling techniques is that they can target more specifically the experiments which are most likely to lead to advances in understanding.

18. CONCEPTUAL DEVELOPMENTS IN THE TWENTIETH CENTURY

As has already been indicated, conceptual developments and the consequent increase in understanding of metallurgical phenomena are largely the result of improved investigational techniques which enable new and fundamental observations to be made. They are essential for the development of improved processing methods and the production of materials with improved properties. As described earlier, conceptual understanding was rudimentary in 1900, being restricted to the idea of the equilibrium diagram and certain applications of the thermodynamics of Gibb and his contemporaries to iron and steel manufacture and to the constitution of steels. Major conceptual breakthroughs had not occurred, although there were speculative concepts in the fields of plastic deformation and fracture, and even the hardening of steel. But the large universal concepts which were to be developed during the twentieth century were unknown, the beauty of such concepts being their widespread application to fields very different from that of their genesis.

18.1 Phase Diagrams and the Crystal Structure of Steel

The ideas of phase diagrams applied to steel were in their infancy in 1900, although the application of thermodynamics in the form of the phase rule was beginning to be appreciated. The major impediment was the lack of knowledge of the crystal structures of the constituent phases, which was not remedied until the application of X-ray techniques for crystal structure determinations after the work of Bragg in
1913. This led to an appreciation of the transformations in steels, as will be described later, and especially after about 1920 of the nature of the occurrence of the interstitial elements in the ferrite (bcc) and austenite (fcc) lattices. This was followed rapidly in the later 1920s and 1930s by an understanding of the structure of the hardened constituent, martensite. Later, this work was extended to other transformation products of austenite and still later to the precipitation of carbides/nitrides and many other compounds, and the effects of orientation relationships between the matrix and precipitates. In addition the concept of crystal structure was extended to preferred orientations and textures which underpinned the whole development of the formable steels in the second half of the twentieth century.

18.2 Dislocation Theory

This is arguably the most important concept of the twentieth century, being applied to a multitude of phenomena widely different from that of its origin. The concept of block slippage, deduced from slip line observations during plastic deformation, was fundamentally questioned by Frenkel's calculation (1926) which showed that the theoretical yield stress of a metal would be one or two orders of magnitude greater than the observed yield stress. The concept of a lattice defect, the dislocation, which allowed the nucleation and growth of a slipped region in the slip plane at relatively low stresses was proposed independently by Taylor, Orowan and Polanyi in 1934. Such lattice defects were at the time unobservable and the concept was not developed further until after the Second World War. Since then it has been applied extensively to every aspect of plastic deformation in metals, particularly steels, and to many other very disparate phenomena. It was realised that the start of plastic yielding was controlled by the stress required to generate or move dislocations, which themselves became visible by electron microscopy after the mid 1950s. Increased yield strengths were perceived to be the result of making dislocation movement more difficult and, as early as 1948, well before dislocations were actually seen, Orowan elegantly showed how particles could impede the motion of dislocations. At the same time other mechanisms to allow dislocation escape from particles by particle shearing were identified, leading to the Mott and Nabarro mechanism of strengthening by coherent precipitates or the solute enriched zones identified by the X-ray studies of Guinier and Preston in the 1930s. This opened up a complete understanding of precipitation strengthening and the effect of precipitate particle size and content, which was developed further by Ashby in 1966 to enable quantitative predictions of dispersion strengthening to be made. The segregation of interstitial solutes (C and N) around dislocations in bcc iron was proposed by Bilby and Cottrell (Cottrell atmospheres) in about 1949 and used to provide the first realistic explanation of the discontinuous yield point in mild steel.

This made possible the explanation of strain ageing and provided the base for the more recent developments of 'interstitial free' and 'bake hardenable' steels of the 1980s and 1990s. At about the same time (1951) Eshelby, Frank and Nabarro cal-
culated the stress ahead of a dislocation pile-up in a slip plane, which was used by Cottrell (1964) to calculate the stress needed to propagate deformation from one grain to another and thus define the lower yield stress. This was used to underpin the experimental observations of Hall (1951) and Petch (1953) concerning the effect of grain size on yield strength and was shown to give excellent predictions by Dingley and McLean in 1967, although, as will be shown later, the Hall–Petch equation had been used in the early 1960s to develop the complementary concept of structure–property relationships.

Since the explosion of work on dislocation theory in the 1940s to the 1960s, the concept of dislocations has been progressively applied to many phenomena. These are too many to describe in detail but the universality of the concept can be appreciated by simply mentioning work hardening, creep, recovery and recrystallisation, fatigue, crack nucleation and growth, phase and precipitate nucleation and growth, the structure of grain boundaries and phase interfaces, shear transformations etc. This has culminated in the latter part of the twentieth century in the deformation and fracture maps of Ashby which have been applied to other processes, e.g. sintering, the grain size of weldments, etc. Rarely can a concept have had such universal application.

18.3 Grain Size Control

The granular nature of iron had been illustrated by Grignon as long ago as 1775 and in the nineteenth century Kelvin identified the tetrakaidecahedron as a regular solid shape which could fill space completely with the angles between surfaces approaching 120°. Interest in cellular (or granular) structures was widespread across metallurgical, physical and biological disciplines and naturally attracted the attention of mathematicians. By 1900 it was well appreciated that fine grained steels, as revealed by fractured surfaces, gave better toughness than coarse grained steels and were stronger. Consequently, in the first third of the twentieth century attempts to grain refine steels were common and Al grain refinement had been introduced well before 1940, although the role of AlN was only just beginning to be appreciated. It was also known by the 1920s that the grain size of steel could be refined by lower hot working temperatures in the austenitic range. C. S. Smith produced in 1949 a conceptual breakthrough by drawing attention to the fact that in all disciplines the grain size was influenced by interfacial energy (surface tension) and posed the question of the effects of second phase particles on the inhibition of grain growth. Zener, a physicist, in 1949 attempted to answer this question with the classical Zener equation, which was semi-quantitative. Subsequent work of Hillert (1965) and Gladman (1966) refined the Zener model, led to quantitative predictions of grain growth inhibition and explained the phenomenon of abnormal grain growth.

From the late 1950s, Nb grain refinement had been exploited followed rapidly by V and more recently by Ti. The role of such particles as Nb(CN), VN and TiN, and of their Ostwald ripening, has been accepted for many years, Ostwald ripening drawing on thermodynamic concepts. In the last twenty years this has been used in
what is known as titanium nitride technology for grain size control, which is applicable to a wide range of steels and their uses. Further advances, already under active investigation, use controlled quantities and sizes of oxidic particles, but this awaits further developments in manufacturing technology before it can be effectively exploited. Another facet of the concept of grain size control has involved controlled thermomechanical processing, i.e. controlled rolling and cooling to refine the austenite grain size and thereby the transformed ferrite grain size. It has been coupled with grain growth inhibition by second phase particles and applied widely to developments in high strength low alloy steels, and also in other steels.

Although the science and technology of grain growth inhibition are now well understood, control of the grain structure formed in steels by heating and cooling through the transformation temperatures (i.e. the allotropic changes) is still somewhat empirical, although serious attempts are being made currently to predict the grain size immediately after transformation. This control of structure, especially by second phase particles, is not confined to bulk steel properties, but is now being used for the control of the structure of weld metals and heat affected zones.

18.4 Structure–Property Relationships

The developments in the mid twentieth century led to the concept of the quantitative correlation between many aspects of microstructure and properties such as yield strength, toughness, ductility, etc. Such relationships were dependent on quantitative metallography and the appropriate constitutive relationships. The basis of quantitative metallography was provided initially by geologists well versed in microscopy and stereology, whilst the individual constitutive relationships were developing rapidly by the mid twentieth century. A natural conceptual development was the integration of the various constitutive equations to give quantitative predictions of specific properties and often combinations of properties, from quantitatively defined microstructures. This concept was pioneered by Gensamer and his co-workers in 1942, relating the strength of pearlite to the interlamellar spacing. In the early 1960s attempts were made to combine the Hall–Petch grain size relationship and the particle strengthening relationship of Ashby and Orowan (mentioned above) with solid solution and dislocation strengthening. Considerable success was achieved with the low carbon ferrite–pearlite structures and with the microstructures containing up to 100% pearlite. In addition, the effect of microstructure on certain toughness parameters was quantified.

The ability to predict properties from microstructure provided an excellent tool for steel optimisation and proved useful in developing not only steel compositions (i.e. the high strength low alloy steels), but also processing methods, such as controlled thermomechanical processing. This was instrumental in pushing the development of steelmaking techniques for delivering reproducible low carbon contents and stimulated the use of thermodynamic concepts to describe microalloy carbide/nitride solubilities. Ductility and toughness were successfully related to inclusion content and shape by Henry and Plateau in 1957, and later to other second
phase particles, such as carbides. Again, there was a stimulation of steelmaking
techniques to modify inclusion shape for optimum properties in the 1970s and ulti-
mately to eliminate inclusions in the later 1970s and 1980s. This work relied also on
thermodynamic concepts.

Success was also achieved with predominantly austenitic structures and the
strengthening equations were supplemented by various predictions of formability,
mainly stretch forming. The methodology has been applied also to other properties,
but with less spectacular success, and often rather more empirically. However,
problems have been encountered in deriving viable structure-property relations-
ships for the higher strength tempered martensitic and bainitic steels, because of
the complex microstructure comprising varying ferrite grain size, dislocation den-
sity and interstitial solute content, and a multi-modal carbide distribution. Such
microstructures are difficult to characterise quantitatively and relationships
obtained are to some extent empirical.

The further development of this concept so that the microstructure can be pre-
dicted from steel composition, heat treatment and processing, and so that the prop-
erties may also be predicted, would enable a complete expert system to be
developed. This remains a challenge for the twenty-first century.

18.5 Hardenability and Transformations

In essence, the concept of hardenability and transformations may be traced back
into the nineteenth century with the appreciation of air hardening (Mushet 1868)
and the influence of alloys on the allotropic transformation temperatures in the
early years of the twentieth century. But the major conceptual innovation arose
from the work of Davenport and Bain in 1930 on the isothermal transformation of
austenite. This stimulated much investigation of nucleation and growth kinetics.
Thereafter, the concept expanded into the ‘Physics of hardenability’ (Mehl, 1939)
and encompassed explanations of the mechanisms of formation of transformed
structures, particularly those of the pro-eutectoid phases ferrite and cementite,
pearlite and to some extent martensite. Phenomenological theories of martensite
formation were introduced in the early 1950s, the mechanisms of bainite formation
after about the mid 1960s and that of pearlite in 1946. The tempering of martensite
proved a more difficult problem, although the investigations of Cohen and his co-
workers in the 1940s and 1950s had made progress in elucidating some of the mech-
anisms. In all these fields, however, there was a marked acceleration in
understanding following the introduction of electron microscopy in the 1950s and
1960s. The work of Nutting and Honeycombe in this period led to a comprehensive
knowledge of the mechanisms of tempering, the nature of secondary hardening
and the formation of alloy carbides. Slightly later in the 1970s (Honeycombe and
co-workers) the mechanisms of interphase carbide precipitation were elucidated
together with the influence of interface structures on the growth of transformation
products. Even more recently the influence of inclusions on transformations is
under investigation with special reference to welded structures, and the exciting
prospect beckons of being able to tailor the inclusion compositions and contents for specific transformations and properties.

18.6 Fracture

Mention has already been made of the concept that microstructure, inclusions and second phase particles can be related quantitatively to certain toughness and ductility parameters. But this does not encompass the concept of a critical defect size which can be tolerated without catastrophic rapid fracture occurring. This concept of a critical defect size originated with the Griffiths crack in glass (1921) but was not applied extensively to steel until the 1950s with its adaptation to ductile material and the development of techniques to measure fracture toughness. This has been extended to consider the sub-critical cracks and their growth to criticality, i.e. the idea of crack growth. The concept has been applied to many situations such as creep crack growth, crack growth under various fatigue conditions, and stress corrosion crack growth. Space prevents extensive coverage of this subject which is so important to engineering design, quality of steels, i.e. inclusion content, size and distribution, the inspection methods required to monitor the integrity of engineering components and the prediction of component life and replacement policy. Undoubtedly this conceptual field will play an ever increasing role in the technology of the twenty-first century.

18.7 Thermodynamic Concepts

Thermodynamic concepts have been progressively applied across the whole discipline of metallurgy during the twentieth century. In 1900 simple thermodynamics had been used to explain the order of oxidation of impurities during steelmaking, and in the simple deoxidation methods used. In equilibrium diagram work, the phase rule was beginning to be used and this continued during the early part of the twentieth century. Mention will only be made of some of the more important developments.

The concept of free energies of formation of oxides, sulphides, carbides and nitrides and their temperature dependence, portrayed in the Ellingham diagram, was an essential prerequisite not only in understanding the production of iron but also in the development of deoxidation practices and in the desulphurisation of both iron and steel which has led to the super clean, super pure steels currently produced. Without this concept, the development of modern steelmaking practices to produce low interstitial contents would not have been possible, nor indeed would have been much secondary ladle and vacuum steelmaking. Also, the use of thermodynamics has been essential for the development of computer control of the steelmaking processes in the last forty years, which has enabled such a large increase in production and productivity to be achieved.

The further application to equilibrium diagrams has enabled realistic solubility boundaries to be established and the extrapolation of diagrams to low tempera-
tures at which experimental equilibration is tedious or even impossible. It has also been essential to use thermodynamic modelling to predict phase equilibrium in complex systems involving many components, which began in the 1970s. This has been specially useful in predicting the sequence of precipitation of carbides, nitrides and carbo-nitrides in the complex high strength low alloy steels containing carbon, nitrogen and all combinations of the microalloying additions Nb, V and Ti, both with and without Al. In addition the compositions and volume fractions of the phases can be established.

Equally important have been applications to assess solubility, by means of the solubility product. Since the early 1970s this has led to an explanation of why properties, such as precipitation strengthening, creep and rupture strength, tempering resistance and intensity of secondary hardening, show a maximum at the appropriate stoichiometric ratio for the precipitating carbide/nitride, whilst other properties, such as creep ductility, show a minimum. This has replaced the previous mystical concept of ‘carbide balance’, so popular in designing some of the earlier creep resisting steels. These solubility effects have also been applied to recovery and recrystallisation, grain boundary pinning, the grain coarsening temperature and stabilisation against intergranular corrosion, to mention but a few. Moreover, thermodynamics have been used to understand the growth of particles by Ostwald ripening (Wagner, 1961), which is essential for developing steels in which there is grain growth inhibition by second phase particles and in which particle growth can lead to a major degradation in properties, i.e. creep resisting steels.

Thermodynamic concepts have also been widely applied to all the transformation reactions of austenite and to precipitation effects. This has led to the ability to predict transformation behaviour, transformation diagrams and even hardenability effects. Perhaps the most recent application of thermodynamic concepts in the last twenty-five years or so, has been the appreciation that solid solutions are not of homogeneous composition and that elements can interact and cluster, that the atoms and clusters can segregate, often to phase interfaces, and that there are site competition effects between elements at interfaces. These have all led to a major understanding of many embrittlement phenomena, such as temper embrittlement, which are impurity controlled. This has led in turn to the accelerated development of the current ‘super pure’ steels for severe service requirements.

19. DEVELOPMENTS IN STEEL COMPOSITIONS AND TYPES IN THE TWENTIETH CENTURY

During the twentieth century there has been a continual acceleration in the development of steel compositions, types and properties, which became particularly intense after the 1940s but tailed off towards the end of the century. It is not unfair to comment that many of the steels, particularly up to the period when electron microscopy and other sophisticated techniques made possible a very detailed understanding of microstructure and its relationship to properties, were not delib-
erately designed with reference to sound metallurgical principles. For example, some steels were produced as a result of arbitrary *ad hoc* alloy additions whilst others came about by serendipity. On the other hand, since the 1950s more and more steel developments have benefitted from sound metallurgical understanding, for example the microalloyed HSLA steels and various creep resisting steels.

It is also true that not all developments reach commercial exploitation, either because they were overtaken by even better alloys or because they were too difficult to control or to be produced economically. Many different generic types of steel were developed almost simultaneously so that a simple chronological account is difficult. The following considers various generic classifications of steel and performance must include reference to the underlying metallurgy.

19.1 Quenched and Tempered Steels

At the turn of the twentieth century most steels were plain carbon steel containing up to hypereutectoid carbon contents, the lower carbon hypoeutectoid steels being used for structural applications whilst the high carbon hypereutectoid steels were essentially tool steels. In 1900 less than 0.5% of steel output was what would now be called alloy steels and the majority of this was tool steels. In the first two decades of the twentieth century, however, much work was done on the effects of alloying elements on the transformation temperatures. In the case of carbide forming elements, the constitutions of alloy carbides were being investigated. Combinations of alloying elements, i.e. Ni–Cr, Cr–V etc. were being investigated from about 1905 and the increased ability to harden by quenching was noted. In fact the ability of Ni–Cr steels to air harden was known from 1909 (Guillet) and the phenomenon of temper brittleness in such steels was known and documented by 1920.

The work of Portevin and Chevenard in about 1920 showed how increasing the cooling rate progressively lowered the transformation temperature and that, at a 'critical cooling velocity', there was a discontinuous decrease in the transformation temperature to a level that did not vary with cooling rate. This was identified with martensite formation. Although alloy steels had been used for military hardware in the First World War, the fundamental work of Portevin and Chevenard set the scene for the study of transformations during the cooling of austenite and resulted in major advances in the development of alloy steels for quenching and tempering. In this period, almost all the quenched and tempered alloy steel combinations were developed, the use of Mo being at last incorporated as the availability of the element increased and the price decreased.

In the 1920s much work was done on the continuous cooling transformations of alloy steels, which gave a further impetus to their development and culminated in 1930 in the classical work by Davenport and Bain on the isothermal transformation of austenite and the identification of the bainitic structure. From then on there was still further impetus for alloy steel development as the isothermal transformation diagrams of all the standard quenched and tempered alloy steels were determined and collected into many atlases. Isothermal transformation diagrams began to be
determined after 1930 at an ever increasing rate, culminating in the publication of atlases from the 1940s, e.g. USS Corp, 1943. Many supplements showing continuous cooling transformation diagrams were also available from about 1950. The method of presenting continuous cooling transformation diagrams in the very practical form of bar diameters cooled in different media was readily available in 1977 (British Steel Corporation). The genesis of the concept of hardenability imparted by alloying elements was the result of this work, the first hardenability tests being proposed about 1930, and the now standard Jominy test in 1938. In addition the beneficial effects of boron on hardenability were discovered in the late 1930s and developed in the 1940s and 1950s, leading to the boron steels in use today.

In the 1930s it was appreciated that martensite involved a shear transformation and the orientation relationships between austenite and martensite were determined by Kurdjumov and Sachs (1930), Nishiyama (1934) and Wassermann (1935). This was also accompanied by the analysis of transformations in the 1930s and 1940s, which led to classical work on the physics of hardenability (Mehl, 1939) and underpinned the systematic understanding of the quantitative effects of alloys on hardenability and their calculation. The result of this work and the compilations of hardenability data led to the reformulation of the compositions of alloy steels in the Second World War to conserve strategically scarce alloying elements.

Parallel with many of the developments in the field of hardenability was the study of tempering which commenced in the 1920s (Bain) and progressed through the 1940s and 1950s with the work of Cohen and his co-workers and was then continued by the intensive use of electron microscopy in the 1950s/1960s. Again, this led to the optimisation of alloy contents especially as after about 1970 the influence of stoichiometry on the solubility and precipitation of carbides/nitrides was understood. In addition, use was made of residual elements from selected scrap to enable increased hardenability to be obtained at no extra cost.

Over the years much work had been done on the various embrittlement phenomena associated with tempering, especially temper embrittlement and the resulting intergranular fracture. The beneficial effect of Mo was known and resulted in the development of the Ni-Cr-Mo quenched and tempered steels, but a more complete understanding of the effects of residual alloying elements such as Sn, Sb, As, P, etc. awaited the development of Auger electron spectroscopy in the late 1970s. This has resulted in the development of the 'super pure' steels after 1980, fortunately aided by the availability of special melting techniques.

19.2 Formable Steels

The increased demand for formable mild steels consequent on mass automobile manufacture and the packaging and white-ware industries from the 1930s onwards led to considerable developments. It should be appreciated that the carbon contents were not so low as now available, so that rimming steels were used which utilised the carbon free surface, with improved surface ductility and freedom from defects,
associated with the rimming action. All steels were made by ingot technology. In
the 1920s the existence of the crystallographic textures in cold rolled sheets had
been demonstrated, and by the 1930s recrystallisation textures had been deter-
dined, whilst the dependence of good deep drawing properties on the intensity of
the (111) texture parallel to the rolling plane had been shown.

Considerable work was then done to optimise the processing conditions to
achieve this desirable texture. But even the nature of discontinuous yielding was
not understood, and consequently nor was strain ageing. It was appreciated that
temper rolling could eliminate discontinuous yielding and the occurrence of
stretcher strains or Luders bands, but this was a temporary amelioration as strain
ageing occurred with the return of the yield point. Thus even up to the 1960s or
later, formable sheet had to be pressed within a relatively short period of time after
temper rolling. After the late 1940s when an understanding of discontinuous yield-
ing and strain ageing was available, Al additions were made to combine with the
nitrogen. The steels thus produced were Al-killed and needed a lower carbon con-
tent, but in the 1960s they were observed especially to have a more intense [111]
texture and better deep drawability than rimming steels, provided the AlN precip-
itated at an appropriate stage during processing. This required a marked modifi-
cation to the processing route, and led to the development of the extra deep
drawing steels in the 1960s.

Similar effects could be produced by other strong nitride forming additions,
which also had the benefit of further minimising strain ageing problems. The Al
treated steels were particularly suitable for production by the continuous casting
techniques then being introduced. About this time, attempts to make deep drawing
steels by the scrap-electric arc steelmaking process ran into problems from high
residual Cu and Sn contents in the scrap which resulted in sub-scale Cu enrichment
causing grain boundary cracking during hot rolling and consequently unacceptable
surface defects. This led to the control of residuals and of reheating temperatures
and conditions. Much progress had also been made in understanding how the tex-
ture development during the annealing depended on carbide/nitride particles,
grain size and both interstitial and substitutional solute contents. Control of these
variables was introduced in the 1970s.

During the period up to the early 1970s batch annealing was the universal
method of annealing, but thereafter continuous annealing was progressively intro-
duced and is now virtually ubiquitous for formable sheet production. Steel com-
position and processing had to be considerably modified, and in particular the
matrix had to be made relatively pure. This led to the use of scavenging additions
to produce the interstitial free steels in the 1980s, although the high ‘r’ values of
these types of steel had been known since about 1950 and certainly were well
appreciated by the late 1960s. Steels containing Ti, Nb, and V were in use by the
1970s.

The demand for higher strength formable steels led to the use of solid solution
hardened steels, using Mn, Si and P which were introduced by the late 1970s,
despite the possible cold work embrittlement by P which restricted its use to below
0.1%. These were also used in conjunction with interstitial free matrices in the early 1980s. This conflicted with the development of higher strength bake hardened steels in the later 1980s. Again changes had to be made to processing and composition to leave a controlled level of carbon, but not nitrogen, in solid solution by using Nb and Ti additions. In attempts to obtain yet higher strength, the microalloyed HSLA steels were produced by cold rolling and annealing in the period 1975-1985, and yet again further control over processing had to be introduced. The best properties seem to be achieved when the austenite is controlled rolled rather than normally hot rolled.

Other developments led to the recovery-annealed steels of higher strength in the 1980s. Such steels were not recrystallised, but careful process control is necessary. All these developments were largely aimed at achieving deep drawability but not necessarily good stretch formability which requires high uniform elongations and a high work hardening rate relative to the yield stress. As early as 1963 it had been shown that this could be achieved by ferrite-martensite structures developed by quenching from an intercritical temperature, but it was not until the mid 1970s that practical interest was taken in these steels. Much work was done in the 1980s on the dual phase type of formable steel to understand the mechanisms involved, and various alloy compositions were investigated together with the effect of cooling rate. In addition, attempts were made to produce the required structures on continuous annealing lines and by direct hot rolling followed by controlled cooling. However, problems of process control resulted in the acceptance of dual phase steels being less than was predicted in their early days, although some components (in automobiles) have been made from them. The developments in stretch forming austenitic stainless steels will be described later.

During much of the last quarter century, formable low carbon sheet steels have been developed using a variety of metallic, non-metallic and polymeric coatings for corrosion protection, packaging and decorative applications. This subject is largely outside the scope of this discussion. However, it can be seen that the modern formable steels bear little relation to the original mild steel sheet of the 1930s and use some of the most sophisticated metallurgical concepts and processing control. Some 50% or more of all steel production is of these steels.

19.3 High Strength Low Alloy Steels

The evolution of these steels constitutes one of the most significant metallurgical developments of the last forty years and has essentially involved the addition of small amounts of V, Nb or Ti (the microalloying elements) singly or in combination to a low C-Mn steel. This coupled with appropriate thermomechanical processing, has in effect doubled the yield stress of a steel comprising predominantly a polygonal ferrite structure, with an accompanying improve in toughness. So successful have been these development, which almost uniquely have been based on sound metallurgical principles and understanding, that they amount to some 10% or more of world steel output.
Over the years the design of HSLA steels has changed greatly. Starting with plain carbon steels containing 0.3 wt-%C, little importance was attached to yield strength, toughness or weldability, the design being based on tensile strength which accounts for the cheap high carbon composition. This was still standard steel up to the late 1930s. However, by increasing the Mn to 1.5 wt-% the yield strength was increased from 250 to 350 MPa.

These steels were successful as no welding was required. By the late 1940s the use of welding and the appreciation of problems due to brittle fracture had been accepted, with a consequent lowering of the carbon content to achieve an increased Mn:C ratio (1947). By the early 1950s the beneficial effect of ferrite grain refinement on the yield stress and the ductile–brittle transition temperature had been demonstrated. The newly developed methodology of structure–property relationships in the mid 1960s hastened the introduction of normalised grain refined steels, which had 75–125 MPa higher yield strengths, together with sub-zero impact transition temperatures. Initially grain refinement used Al–N additions, which had been introduced well before 1940, but later other grain refining additions such as Nb, V or Ti were used and found to contribute to precipitation hardening. In fact Nb additions had been investigated in the early 1940s but economic considerations prevented it from being commercially exploited until the late 1950s. The significance of NbC solubility in the austenite and the effectiveness of vanadium in precipitation strengthening of normalised steels because of the high VC solubility in austenite, was established in the 1960s. Multiple microalloy additions, i.e. Nb–V, V–Ti etc. were used from the mid 1960s onwards.

The toughness of Nb steels suffered because of their coarse as-rolled austenite grain size and consequent ferrite grain size, as well as due to precipitation strengthening. The solution to the problem was controlled rolling at low finishing rolling temperatures developed in the 1960s, and very many variants of rolling schedules, often specific to a mill, were introduced over the ensuing years. Developments in controlled rolling still occur, as for example, recrystallisation controlled rolling in and after the mid 1980s. This owes its effectiveness to the development of TiN technology by which small Ti additions effectively maintain a very fine austenite grain size, even when finishing rolling at high temperatures, so allowing sufficient of the microalloy carbide to remain in solution to enable precipitation strengthening to occur. These developments allowed yield strengths up to 525 MPa to be produced with impact transition temperatures as low as −80°C. The development of controlled or accelerated cooling of either plate or hot rolled strip followed rapidly, which decreases the ferrite grain size and produces more precipitation strengthening by a finer precipitate size. The accelerated cooling process was first used on the run-out table of hot strip mills from about 1960, initially for narrow strip, but is now used on wide strip mills. The accelerated cooling of thick plates is less easy, but was developed from the mid 1970s.

Controlled rolling can lead to increased elongation of the MnS inclusions and consequently increased anisotropy of ductility and toughness. Techniques of inclusion shape control to modify the MnS were developed in the late 1960s, often to
eliminate lamellar tearing during welding. The technology was, however, rendered unnecessary by the development of very cheap and efficient desulphurisation during steelmaking, particularly by the use of Ca additions. These are still widely used today to desulphurise and to alter the alumina inclusions to calcium aluminates thereby eliminating nozzle blockage problems in continuous casting.

In the 1960s the use of low carbon ‘pearlite-free’ steels was pioneered but bulk steelmaking practices could only produce carbon contents of 0.03–0.08%; the ‘pearlite reduced steels’. Modern steelmaking can lead to consistently very low carbon and nitrogen contents which allow very small microalloy additions to precipitate carbonitrides and to produce an ‘interstitial free’ steel. These have been described under the section of formable steels, and are not HSLA structural steels, but a similar concept to reduce strain ageing has been used for earthquake resistant structural steels.

Another type of HSLA is the acicular ferrite steel. These were originally based on the low carbon (0.12/0.15%) bainitic steels developed in the late 1940s and the 1950s, which had proof stress values of up to 450/900 MPa. The higher strengths were obtained by using much higher carbon contents. These steels will be discussed later. In all the original bainitic steels the transformation characteristics were controlled by alloying additions, i.e. 0.5%Mo–B to allow low carbon bainite to form over a wide range of cooling rate from the rolling finishing or normalising temperature. However, their toughness was inferior due to the large carbides in the upper bainite structure at the carbon contents then available. In the late 1960s it was appreciated that a considerably lower carbon content, ~0.02%, would materially improve the toughness. These steels were developed by the Climax Molybdenum Corporation in the early 1970s to form the commercially successful acicular ferrite steels and controlled rolling and cooling techniques were applied quickly to them. At the same time low carbon steels containing up to 4.5%Mn, the FAMA steels, were developed with Nb and/or V additions to produce grain refined, precipitation strengthened, acicular ferrite steels. The acicular ferrite steels never achieved major use, although small amounts are made even today.

The success of HSLA type steels is shown by the fact that some 10% of all steel production is of this type. Further usage of microalloyed (HSLA) steels is limited by the fact that many steel applications are modulus dependent and the modulus is unchanged by microalloying additions.

19.4 Medium-High Carbon Steels for Rails, Rod, Wire, Bars and Forgings

These steels traditionally contain from 0.3% to above eutectoid carbon content with no specific alloy additions other than Mn although, more recently, small amounts of the microalloying elements have been made. From the early days of the century they have been used as railway materials (e.g. rails, wheels, tyres, axles) and have also been used for drawing into high tensile wire. With the advent of concrete for civil engineering they have also been used as reinforcing bars and rods, and have found use as forgings for various components in automobile engines.

The main property requirements are strength, fatigue resistance and wear resist-
ance, but since the 1960s they have also required a measure of ductility for the manufacture by cold heading of high strength fasteners, bolts, etc. Also increasingly stringent toughness requirements became evident. These improvements led to thorough investigations in the early 1970s into the quantitative structure-property relationships which shows that the dilution of the pearlite to contain less than eutectoid carbon by lowering the transformation temperature, which also produced finer polygonal ferrite grains, could substantially improve the toughness, and that there was an optimum pearlite interlamellar spacing for good toughness. In addition it was shown in the 1970s and 1980s that the pearlite colony size controlled fracture and that fine pearlite colonies produced from grain refined austenite, or thermomechanically worked but unrecrystallised austenite, could be beneficial for toughness. An addition of the microalloying element V could also increase the strength by precipitation strengthening by VC.

In rail steels, improved fracture toughness was produced in the 1970s by the use of grain refinement, normalising or controlled rolling, although the latter is not easy to control in view of the large differences in section dimensions. In wire rods, the use of controlled processing by, for example, the Stelmore process, produced initial microstructures more conducive to heavy wire drawing reductions, and various patenting processes achieved the same result. The resulting higher drawn strength has been utilised in both wire rope and in fine wire for tyre cord, and in the 1980s small alloy additions, such as 0.25%Cr, 1%Si or 0.1%V, were used, which gave an increase in strength of about 100 MPa as a result of precipitation strengthening. But perhaps the most significant improvement, especially with regard to the drawing of very fine wires for tyre cord has resulted from improvements in steel-making practices. In the 1960s the elimination of the larger silicate inclusions by effective aluminium deoxidation was an important development and more recently the use of Ca treatment has been beneficial not only to desulphurise but also to change the hard undeformable alumina, spinel and calcium hexaluminate to the more acceptable and often smaller calcium aluminates less rich in $\text{Al}_2\text{O}_3$. These improvements have continued into the 1990s.

The manufacture of fasteners, such as high tensile bolts from medium carbon steels, requires ductile rod or wire that can be fabricated by cold heading. This was achieved in the 1960s to 1980s with carbon contents in the range 0.30–0.45% and, whilst some alloy steels were used to give increased hardenability and tempered martensite structures, more recently moves have been made to omit the hardening and tempering and to replace the strength lost thereby by enhancing work hardening during cold heading. Equally the principles involved have been applied to the tendons for pre-stressed concrete and for improved coiled springs. In these applications the need to guard against stress relaxation has been realised by ageing or stress relieving at 200°C.

Interesting developments have been made in the field of forgings for automobile engine components which traditionally were made from quenched and tempered steels. In the 1970s and 1980s there was a change to austempered ductile irons which, whilst being cheaper, still required heat treatment. The cheapness was
engendered largely by casting to 'near net shape', removing primary working and forging costs and some machining costs. Microalloyed V treated medium carbon steels which were controlled cooled after forging could, however, produce the required tensile and fatigue strength, employing a ferrite-pearlite structure strengthened by V(CN) precipitation. Many forgings had complex shapes and forging strains were inhomogeneous; hence control of grain size was essential. This was achieved through the use of TiN technology and was helped by steelmaking developments in the 1980s and 1990s which allowed controlled and reproducible Ti contents of 0.01% to be obtained. There have also been very considerable developments in the field of free machining steels, not only by the addition of S, Pb, Bi, Te and Se, but also by control of the ferrite and pearlite distribution. This has resulted in reduced tool wear and increased production rates.

19.5 Bainitic Steels

The first deliberate commercial use of bainite occurred in the 1930s with the austempering treatment, following the work of Davenport and Bain on the isothermal transformation of steel. Originally conceived to reduce distortion and cracking, austempering could only be applied to steels of certain compositions and types of isothermal transformation diagrams, but transformation of some steels to lower bainite resulted in improved ductility and toughness for a given strength. The low carbon (0.12/0.15%) bainitic steels were discovered (1949) by chance when boron was added to 0.5%Mo superheater tube material to improve the creep rupture ductility. The yield (proof) strength was found to be 50% higher than that of the boron-free steel in the normalised or as-rolled conditions.

It became apparent that the steels had potential as weldable high strength structural materials and might rival the microalloyed HSLA steels. This was not to be the case, but during the 1950s and 1960s much development work was carried out and the steels were marketed. By alloy additions, especially of Mn and Cr to the 0.5%Mo-B base, a range of proof stresses from 400–900 MPa was possible which could be achieved by the air cooling of sections up to 25 cm dia. Attempts were also made in the 1960s to improve the strength by controlled rolling, by ausforming and by introducing precipitation effects by microalloying with Nb and by Cu additions. The main drawback to the steels was their low toughness consequent upon the large carbides present in the low carbon upper bainite. The steels never achieved widespread acceptance and were out-performed in toughness by the development of the very low carbon acicular ferrite steels as the beneficial effects on toughness of carbon contents as low as 0.02% were realised.

If the weldability requirement was relaxed it was believed that higher carbon bainitic steels might rival certain quenched and tempered steels without the cost of heat treatment or the risk of quench cracking and distortion. In the mid 1960s such compositions containing up to eutectoid carbon were developed, but as the B effect on hardenability decreases to zero at eutectoid carbon, it was found that the bainite could only be produced by air cooling over an ever decreasing range of cooling
rates, and at the higher strengths the ductility and toughness was not as good as in the best quenched and tempered steels. Interestingly there seems to have been a resurgence of interest in bainitic steels using Ni, Cr and Cu as alloying additions, in the 1990s.

19.6 Ultra-High Strength Steels

Ultra-high strength steels are usually regarded as having proof stresses in excess of 1400 MPa. Their major uses are in applications such as aircraft undercarriages, high strength bolts and fasteners, some types of pressure vessels, rocket bodies and motor cases, springs, high speed rotors, bearings and shafts, machine parts etc. After about 1950 the demand for ultra-high strength steels became apparent, and their development was aided by the increased understanding of martensite and tempering reactions. Because such high strengths are often associated with notch sensitivity, freedom from internal stress raisers such as non-metallic inclusions became essential and fortunately, in the late 1950s and 1960s specialised melting techniques such as vacuum induction melting and electro-slag refining became available. These techniques not only resulted in much cleaner steels but also in higher purity (lower S, P and residuals) which helped combat embrittlement effects. The development of these processing methods continued over the years, resulting in the ‘super pure’ and ‘super clean’ steels available, at a cost, at the end of the twentieth century. To obtain the strengths required, starting with a martensitic structure in a conventional steel, 0.3–0.4%C is necessary. Lower carbon or even essentially carbon free martensite can be used if an intense age hardening reaction is employed, as in the maraging steels, which will be considered later. Essentially two development routes were used. The first employed tempering at low temperatures of the order of 300°C in steels containing Ni–Cr–Mo additions to give the required hardenability. But the tempering resistance had to be increased in order to use tempering temperatures above 300°C at which a ductility minimum was observed. The mechanism of this embrittlement (tempered martensite embrittlement) was not fully understood at the time (the late 1950s) but as the embrittlement tempering range was being avoided, this was not a serious drawback.

The use of enhanced tempering resistance also allowed tempering temperatures above the embrittlemcnt range to be used without loss of strength. The increased tempering resistance was produced by additions of up to 2.5%Si and/or 1%Co. Thus, by the 1960s, the Hi-Tuf and Super Hi-Tuf types of steel were available. In the early 1960s other additions, such as high Ni and Co, were also suggested, as were Mo–V steels with Si and Cu additions, but these never achieved extensive commercial production.

The second development route used secondary hardening steels, essentially with 1–5%Cr and 0.3–0.4%C, depending on the hardenability required, with additions of up to 2%Mo and 0.75%V to give the required secondary hardening. Ni had to be omitted as it accelerates tempering, but up to 1%Si was used to intensify secondary hardening. These steels, developed in the 1960s, were tempered into the
overaged condition to avoid the catastrophic loss of toughness when tempered to maximum secondary hardness, and essentially became the basis of the Cr–Mo–V tool steels for dies, etc. In the later 1960s, 9%Co, 4%Ni steels secondary hardened by Mo and V were developed and, even as late as the 1980s and early 1990s attempts were being made to further develop the secondary hardening steels by optimising stoichiometry in a 10%Ni, 14%Co, 2%Cr, 1%Mo steel containing about 0.2%C. Fracture toughness was now a consideration, as the low C and high Ni indicate. However, no real commercial developments resulted from these studies. The long established steels still are in use at the close of the twentieth century.

During the 1960s much attention was given to the ausforming process for increasing the strength of quenched and tempered steels, which was also applied to the ultra high strength steels. Very high proof stresses up to 2800 MPa were obtained but required such high deformations of the austenite at temperatures around 500°C prior to quenching and tempering that very limited use of the technique was made. Many other methods of increasing the strength were suggested but never achieved commercial viability.

Also in the 1960s a different type of ultra-high strength alloy was developed which combined proof stress values in the range 1300–2100 MPa with exceptionally high fracture toughness. These steels were based on <0.03%C Fe–Ni alloys containing between 17 and 19%Ni with 7–9%Co and 3–5%Mo which caused age hardening when the low carbon martensite was aged at 480°C. This age hardening was accentuated by additions of up to 0.15%Al and between 0.2 and 0.6%Ti. The steels were often double vacuum melted to give great cleanness and purity with small B, Zr and Ca additions to scavenge impurity elements. The manufacturing costs were very high but the alloys are still in limited use at the end of the twentieth century. Higher Ni–maraging steels containing 20% and 25%Ni were also developed and, instead of Co-Mo age hardening, this was accomplished simply by 0.5%Nb, 0.25%Al and 1.5%Ti. Difficulty was experienced with control of the formation of martensite, because the $M_s$ temperature was below about 150°C. Consequently their use was limited and none of these higher Ni maraging steels are made extensively today.

Mention may be made of a corrosion resistant ultra-high strength steel containing ~ 0.10%C, 12–15%Cr, up to 6%Mo and 5–13%Co. This readily transformed to martensite and was aged hardened by the precipitation of Mo-Cr-Co intermetallic compounds. A very limited application of this type of steel with yield strengths of up to 1300 MPa was found in aerospace applications.

19.7 Creep Resisting Steels

The first steels used for creep resistance were the C–Mn steels employed for boiler plate, piping and tubing in the 1920s and early 1930s. They were even used as rotors in the early power generation plant. Problems were encountered as steam temperatures increased and also with regard to the control of the interstitial nitrogen content, which was a major strengthening element, owing to its reaction with
the deoxidants Si and Al. These steels were still in use in some power plant even in the early 1950s but from the late 1930s tended to be progressively replaced as superheater tubes and headers by the 0.5%Mo steels, which experienced problems owing to low creep rupture ductility. Thus over the period up to 1950 the 0.5%Mo steels were replaced by the 1%Cr–Mo steels which, in a higher (0.3%) carbon version were also used as bolting materials.

As steam temperatures further increased, there was a progressive change to more creep resistant steels in the 1950s and 1960s, such as 2.25%Cr–Mo for tubing and piping and the 1%Cr, 0.5%Mo, 0.25%V steels for rotor casings and steam chests. In this period also there were developments in bolting steels, which moved from 1%Mo in about 1950 to 1%Cr–Mo–V later in the decade and then to similar steels with stiochiometric V:C ratios in the 1960s.

Surprisingly the 5%Cr–Mo steels never achieved popularity, but were used for tubing in petrochemical plant, replacing the earlier 0.5%Mo and 2.25%Cr–Mo steels. By the 1960s, however, advanced 9%Cr–Mo tubing was in use in power plant and in petrochemical plant tubing, as they were quire resistant to sulphur attack. In the 1960s also there were further developments in bolting materials based on 1%Cr, 1%Mo, 0.7%V with Ti and B additions to improve rupture ductility and these developments have continued incrementally to the present day. Advanced bolting materials comprising the complex austenitic steels containing 15%Cr, 10%Ni, 6%Mn with Mo, V and Nb additions then began to be introduced, sometimes in the warm worked condition. The 12%Cr–Mo steels started to be used also for boilers and tubes from about 1970 and, with additions of V and Nb, as rotor blading. After this time virtually the whole of the turbine assembly was in 12%Cr based steels.

Austenitic steels of the AISI316, 321 and 347 types, the latter two being developed originally in Germany in 1929 but not for creep resisting purposes, began to be introduced for power plant tubing, piping and headers from the 1960s and were followed by the use of complex austenitic steels containing multiple alloying additions, together with the 35%Ni, 20%Cr, Alloy 800. The 20%Cr, 25%Ni steels with Ti additions were used for fuel element cladding in atomic reactors, and quite recently the nitrided titanium bearing steels have been used for this purpose. AISI316 and 347 have also been used for steam chests, and many austenitic stainless steels have been used where creep resistance is required in petrochemical plant.

In the last decade of the twentieth century there have also been developments aimed at rotor applications, using 2%Cr, Ni, Mo, W, V for rotors and also by the addition of refractory metal alloying elements such as W, Ta, Nb etc. to the 12%Cr steels, often with enhanced nitrogen contents. It had long been recognised that microstructural degradation should be minimised during creep service and to this end, in the 1970s, moves were made to limit Ni contents in the transformable ferritic steels to ~ 0.6%, because Ni had been shown to decrease tempering resistance.

Creep resisting steels have also played a major role in the development of aircraft engines. Up to the development of the gas turbine in the 1940s, normal quenched and tempered steels were used for many engine components, including
valves. The advent of gas turbines, however, provided a great incentive for the development of creep resisting steels in the 1940s to 1960s starting with the 0.4%C, 13%Cr, 13%Ni, 10%Co, 2%Mo, 2.5%W, 3%Nb steel (G18B) for turbine discs and the use of 12%Cr-Mo-V-Nb steels also for discs and sheet. Other alloys such as a Ni_3 (AlTi) age hardening austenitic alloy (A286) and a 15%Cr, 30%Ni, 1.8%Ti austenitic steel (Tinidur) were also used. The progressive increase in temperature of the engine in the last thirty years or so, has led to almost the complete replacement of steels by the nickel base alloys, often with novel processing procedures, such as mechanical alloying, directional solidification and single crystal blades.

In the last half century particularly there has been a revolution in the understanding of creep deformation and fracture processes, and of the influence of microstructure on them. Thus the steel developments, particularly since about the 1960s have been based on sound metallurgical principles and have rarely relied on chance discoveries. Space prevents any lengthy consideration of these but a few of the more important ones may be mentioned. First was the appreciation of solid solution effects on creep strength, quickly followed by an understanding of how precipitation of carbides influence not only creep strength but also creep ductility. The role of the interaction between substitutional solutes such as Mn, Cr, Mo, V and Nb etc. and the interstitial solutes C and N led to an appreciation of how this affected the creep rate by the mid 1950s. The influence of microstructural stability, particularly on the long term creep and rupture strength was also understood. An important step forward was made by the understanding of how grain boundary particles, mainly carbides/nitrides but also sulphides and, more recently, the role of impurity elements, influenced creep ductility, which led to the use of ESR and VAR melting processes. The most recent advances have been associated with the assessment by modelling and other techniques of the life expectancy and creep crack growth rates. This is vitally relevant to remnant life both within and beyond the design life, as this affects inspection schedules and component replacement policies.

**19.8 Tool Steels**

The second half of the nineteenth century saw the development of machine tools by the developing engineering industries, but there had been little change in the materials being machined so that high carbon tool steel, hardened and tempered, still had to answer all the tooling requirements. The limitations of carbon tool steels were, however, becoming an obvious constraint on production speed. Steels, and particularly the developing alloy steels, were proving difficult to machine. The work of Mushet in 1868 paved the way for the development of W bearing tool steels and the realisation that these could be air hardened. Brustlein in 1886 showed the beneficial effect of Cr in achieving air hardening. In 1900 high carbon tool steels were still predominant in the domestic market (scissors, knives, razors), in wood and metal working and in agriculture (crop cutting). A high C, 8%W, 4%Cr steel was produced in 1900 and by 1906 a composition not much different from the current T1 steel was developed. V additions were patented in 1904.
By 1910 the T1 composition had virtually been reached. Within the next ten years improvements were brought about by adding Co and it was also shown that Mo could effectively substitute for W if precautions were taken against decarburisation. Thus by the 1920s, the M type steels based on 0.80–1.3%C, 4%Cr, 5–8%Mo, 2–6%W, 1–4%V and up to 10%Co were in use. But developments were also being made to the lower alloy steels with quenched and tempered structures, with the additions of relatively small amounts of Cr, Mo, W or V, often in combination, to cater for better cutting properties and other aspects of metal forming, such as forging dies, moulding dies, various shock resistant applications and more recently extrusion dies. These developments proceeded into the 1930s along with the development of increased hardenability steels and, as special requirements arose, continued into the last quarter of the twentieth century. For example, in hot work die steels there have been suggestions of lower Cr contents, the addition of up to 1%Si and increases in Mo up to 2% or more, with optimisation of the V:C ratio to approach stoichiometry. So prolific were many of these developments that literally hundreds of lower alloy tool steel compositions were marketed and by 1972 in the UK alone some thirty suppliers were offering over 200 grades of just the high speed steels. Clearly some rationalisation of compositions was necessary and this was provided by the AISI classification system (1978). Space does not allow the incremental developments in all the different grades to be itemised. Suffice it to say that the water hardening grades containing 0.6–1.4%C and sometimes 0.25%V have low hardenability which can give a tough core. They are tempered at about 200°C and are used for cutting tools, dies, drills, taps and punches and also for surgical instruments. An interesting development since the 1960s has been the use of 6–8%C with 0.6–0.8%C steel for razor blades, not so much to provide the publicised stainlessness but rather to increase the tempering resistance so that anti-friction coatings may be cured without loss of hardness. Further modifications to prevent the formation of large carbides that could chip from the finely honed edge have also been made.

The shock resistant steels, hammers, chisels, shear blades etc. are largely 0.5%C grades with additions of up to 1.5%C, 2%Si, 1.5%Mo, 2.5%W with 0.3%V (i.e. the ultra-high strength steels) and their higher hardenability allows them to be oil quenched and tempered up to 350°C. On the other hand, cold work steels for blanking and forming dies essentially are high C with additions of up to 0.5%C, 0.5%W and 1.75%Mo. They are also oil quenched and tempered to the desired hardness. Other cold work steels with greater wear resistance, containing 1.2%C with 12%Cr and up to 1% of either Mo or V, are used for crushing and grinding. These are air hardened and must be refrigerated at -75°C/ -196°C before tempering to the required hardness. The advent of plastic moulding and zinc die casting led to steels containing lower C and 5% Cr, 0.75%Mo and 0.3%V, and may contain 4%Ni or Co. In order for corrosion resistance to handle some plastics, 12%Cr steels have been used. Hot work die steels for drop forging, stamping and extrusion are conventionally the 5%C–Mo–V ultra-high strength steels. Mo steels with 4%C, 5–8%Mo and 1.2%V, or W grades with 0.25–0.65%C, 3–4%Cr, 9–18%W and up to 1%V have also been used.
The standard W or Mo high speed steels have already been described, and a combined W–Mo type is quite popular. In the 1980s, coupled with the discovery of relatively pure Nb ores in Brazil, Nb and Ta additions were made to high speed steels. Whilst these types are made especially in South America, they have little or no advantage over the more standard compositions. It should also be mentioned that maraging steels have been used since the 1980s for some moulds and dies.

During the second half of the twentieth century much progress has been made in optimising heat treatments to produce secondary hardening, the best distribution of carbides and general tempering resistance. In addition processing developments to control the as-cast structures of high speed steels and carbide segregation have been made, including electroslag refining, vacuum arc refining and spray deposition methods involving accelerated solidification. Whilst not strictly steels, the development of sintered carbide machine tools has had a repercussion on the high speed steel market for more rapid machining and greater production speeds. The carbide tool materials were then challenged first by ceramic tools, e.g. Al₂O₃ and then by the use of surface coatings since the 1980s to produce increased wear resistance. TiN is a favoured coating but others have been developed using physical vapour deposition and chemical vapour deposition. It is in this field of surface engineering rather than in the development of improved cutting tool steels that further progress is most likely. But the effect on high speed steel production has been pronounced. In 1972 there were some thirty UK suppliers of high speed steels, whereas at the close of the twentieth century they can probably be counted on one hand, and the majority of such steels is imported from Sweden, Germany, Austria and the USA.

19.9 Stainless Steels

The world production of stainless steels probably is of the order of 15 million tonnes per year, yet arguably they comprise a unique class of steel with proof stress values in the range 200–2000 MPa and a temperature range of application from −200°C to >1000°C under widely varying oxidation and corrosion conditions. The main drawback is their cost, but so sophisticated is their metallurgy that the major production is carried out in about a dozen highly specialised plants. The history of the development of the stainless steels is by no means unequivocal as work on chromium additions to steel had been going on ever since Faraday and Berthier in 1820–1821, often with conflicting results and opinions. By 1900 the detrimental effect of carbon introduced by high carbon ferro-chromium had been recognised and by 1911 Monnartz had shown, and his work was widely recognised, that Cr imparted corrosion resistance under conditions leading to passivation.

The first commercially produced stainless steel was due to Brearley (1912) although the patent was a year or two later. This was a martensitic 13%Cr, 0.25%C steel, but other workers had been engaged concurrently on these types of steel and Osmond and Hadfield came close to discovering stainless steel in 1892. Carnot, Gautal, Guillet and Geisen had examined Cr alloys in the period 1898–1909, which
had structures probably of ferrite, austenite and martensite. The discovery of the austenitic stainless steels was by Strauss and Maurer in 1912–1914 and by the latter date increasing quantities of a 0.25%C, 20%Cr, 7%Ni austenitic steel were being made by Krupp. Also in 1911 at GEC Dantsizen and Beckett made an alloy of Fe–14/16%Cr for lead-in wires for electric light bulbs, but apparently without recognising its potential for corrosion resistance. It was rapidly realised that these ferritic steels could be increased in Cr content to get improved corrosion resistance, but their acceptance commercially was restricted by the carbon content owing to cheap, low carbon ferro-chromium not being available. Thus by the early 1920s all the main types of stainless steel had been developed and progress became relatively rapid. By the late 1920s and early 1930s the role of carbide precipitation on intergranular corrosion had been established, but not the mechanisms involved, which were proposed in 1937. Nevertheless in 1929 the use of Ti and Nb stabilisation was developed in Germany and these steels, together with the Mo bearing steel, became adapted for high temperature and creep applications. In the 1930s also there was continuing understanding and development of the fully ferritic steels. Thus thirty years after the production of the first stainless steels, all the major types had been developed in essence, and enshrined in the AISI classification.

After the 1940s many developments occurred. In the martensitic grades, the high carbon tool steels have already been discussed but there were major developments in the lower carbon (0.10–0.20%), 12%Cr steels for structural and aircraft applications. By 1960 the tempering reactions had been clearly elucidated, and alloying by Mo, W, V and Nb introduced to increase the tempering resistance. Further alloying with up to 3%Ni eliminated delta ferrite to improve strength and ductility, and the complex constitutional interactions of the alloying elements had been understood. Major uses of these steels were introduced into petrochemical and chemical plant, power generation, aerospace, aircraft engineering and high strength corrosion resistant fields over the ensuing years, and continues today. Attempts to introduce intense precipitation hardening into the 12%Cr steels to produce an analogue to the maraging steels never became accepted owing to cost and low toughness/ductility.

Higher Cr, 14–17%, martensitic steels for greater corrosion high strength applications required some Ni to offset the ferrite forming tendency of the higher Cr content. As early as the mid 1940s 14–17%Cr–Ni steels, sometimes with up to 5%Mn, alloyed with Mo, Al, Ti, Co and Cu, either singly or in combinations, had been developed to control the Ms/Md temperatures. This enabled the steels to be cold formed prior to transformation to martensite. The martensite was then tempered, during which process some of the additions caused precipitation hardening. Proof stress values up to 1400 MPa were achieved in what became known in the 1950s and 1960s as the ‘controlled transformation’ stainless steels. Despite a few applications, difficulties in the control of the transformations limited their use and resulted in the controlled transformation behaviour being abandoned. They became the higher Cr precipitation hardening (PH) steels for high strength in more corrosive environments.

A further development of essentially controlled transformation steels in the later
1960s was to increase the C content to about 0.3%C and by so adjusting the alloying elements to control the $M_d$ temperature to apply thermomechanical processing at 250–550°C and then transform the austenite to martensite by deformation at room temperature, often during forming, followed by tempering or ageing if necessary. These transformation induced plasticity steels (TRIP) could give proof stress values up to 2000 MPa and increased ductility. However, the compositions were complex, often containing combinations of 9%Cr, 9%Ni with Mn, Si and Mo, and were difficult to control as also were the transformation characteristics, so that the costs were high and the form of the material was restricted to flat rolled products or wire. Whilst potential applications for these ultra-high strength stainless steels were suggested, they never became a viable commercial product.

Few developments took place in the fully ferritic 15–30%Cr steels prior to the 1940s but the role of Cr and the interstitial elements C and N on ductility and toughness was appreciated. Ni could not be added if the largely ferritic structure was to be preserved. The availability of low carbon ferro-chromium and the introduction of the AOD and VOD processes from the 1960s, coupled with the periodic shortages and high cost of Ni, gave a boost to 17–18%Cr ferritic steel developments as an alternative to the austenitic steels. One of their major advantages, apart from cost, was their greater resistance to chloride induced stress corrosion cracking than the austenitic steels, but they still had severe disadvantages in terms of a fracture transition, lower general formability and weldability, and in general less corrosion resistance than the austenitic steels. In the ensuing two decades, Mo additions were introduced, and sometimes high Mo contents could allow up to 4%Ni to be accommodated, whilst the C and N contents were greatly reduced to produce the ‘super ferritic’ stainless steels with improved toughness, corrosion resistance, ductility and weldability. Ti and Nb additions were also made both for stabilisation and for the control of the ‘roping’ phenomena, a texture induced defect. They are now widely used in chemical, food, domestic, catering, architectural and transportation applications and, since the 1980s, in seawater cooled condensers, desalination plant and heat exchangers. The higher Cr alloys (up to 35%Cr) have always had a small continued application as high temperature oxidation resistant steels.

For seventy-five years since the 1920s the austenitic steels have been by far the most widely used stainless steel comprising 70–80% of world stainless production. They contain 16–25%Cr and 7–20%Ni and, since the 1930s, the use of Ti and Nb stabilisation, and of Mo, have been commonplace. The development of vacuum and low pressure techniques in the 1960s enabled the carbon contents to be so much reduced that current austenitic steels rarely show intergranular corrosion even without Nb/Ti stabilisation. Stabilisation is largely unnecessary yet AISI types 321 and 347 are still commonly used. The higher Cr contents may exceed 35% for heat resistance and, for some creep resisting steels, require to be constitutionally balanced by higher Ni contents of up to 30–35%, when they approach the iron-based superalloys.

During the 1960s many attempts were made to increase the rather low proof stress of the austenitic stainless steels by solid solution strengthening and by pre-
cipitation hardening. Nitrogen was found to be a most effective solid solution hardener and up to 0.5% was introduced into some proprietary steels, which virtually doubled the proof stress. Precipitation effects were introduced by additions of C, N and P, and whilst some proprietary steels were developed, they never achieved substantial use. On the other hand, intermetallic compound hardening by Al and Ti additions to produce proof stress values in the aged condition of over 700 MPa were successful and, whilst these steels were not widely used, they did form the basis of some of the iron base superalloys for high temperature creep resistance.

Nitrogen was also used with Mn partially replacing Ni to produce a whole series of austenitic steels, the AISI 200 series, in view of the recurrent Ni shortages and high price. These steels had greater work hardening rates by virtue of their lower stacking fault energies and their stretch formability could be better than the standard AISI 304 steel but they displayed somewhat decreased deep drawability. Their corrosion resistance was also rather less, and consequently they are little used today. In the 1980s, however, an interesting development was introduced to improve the stretch formability of the AISI 300 steels. By using the composition to control the $M_d$ temperature at which martensite forms on deformation, a high rate of work hardening could be achieved with the result that the uniform strain could be increased and thereby stretch formability. Whilst no new alloys were developed, since the 1980s this approach has been used to select or optimise compositions for optimum stretch formability.

In terms of corrosion resistance, elements such as Cr and Mo increase the passive range of corrosion potential, hence the advantage of AISI 316 over AISI 304 in oxidising conditions. Ni and Cu can also be useful to induce passivity, hence the increased general corrosion resistance of the higher Cr and Ni compositions. In terms of reducing pitting corrosion, Cr was long known to be effective but in the last twenty-five years Mo and N$_2$ have been found to have a similar effect. This has led to the development of Mo–N additions. Austenitic stainless steels have also long been known to be susceptible to chloride induced stress corrosion cracking, and Mo additions as in the AISI 316 composition are beneficial. Stress corrosion susceptibility was also known to be pronounced at 8–10%Ni, but reduced in higher Ni alloys. This resulted in the 1970s in the development of increased Ni alloys containing Si additions.

A relatively recent development in the 1970s was that of the duplex ferrite–austenite stainless steels, although they had been known for almost forty years. These duplex stainless steels have compositions which develop a constitution comprising almost equal proportions of delta ferrite and austenite. The steels were originally conceived as a super plastic stainless steels, although this potential has not been realised to any great extent. The delta ferrite, however, gives increased proof stress values and improves the stress corrosion resistance, although decreasing the general toughness. The appropriate structure can be achieved in a wide range of compositions which are usually lean in Ni and with Cr contents generally in the range 18–30%. Additions of Mo are used, together with stabilisation by Ti or Nb. A recent development in the last 10–15 years has been the introduction of nitro-
These steels are readily hot worked and easily welded, being used also as a casting alloy. Applications are as plate and tubes in chemical engineering, and as heat exchangers, but their use is steadily increasing. Finally, mention may be made of stainless strip from powder metallurgy processing which has not yet been fully developed.

During recent years there has been a plethora of stainless steel developments and patented proprietary compositions, as the stainless manufacturers have striven to fill ever more stringent and specific applications. Not all have been successful and indeed some developments have been overtaken by newer and better steels. There is now a need for some rationalisation of the many compositions not only to optimise them but also to eliminate the many near duplications which have arisen.

19.10 Cast Irons

Cast irons are essentially iron-based alloys containing the major elements C, Si, Mn, S and P, minor or trace elements such as Al, Bi and Sb, elements such as Mo, Cr, Ni, Cu and Sn used to control the matrix structure and inoculants such as Mg, Ce and Ti which are used to control the graphite morphology.

At the turn of the twentieth century the major types of cast iron, namely grey, white and malleable, had been available for many years (e.g. the white heart malleable irons from 1722 and black heart from 1820) and British Standard Specifications for general purpose irons, 1977–1986, still refer to these categories. Relatively little development was evident in the first fifty years of the twentieth century, but this changed with the discovery in the 1950s of the role of inoculants on the morphology of the graphite. This resulted in the development of the spheroidal graphite cast irons, which largely replaced the malleable irons. Knowledge of how minor additions and solidification influenced graphite morphology led to various new types of graphite structures. The action of alloying and minor elements was appreciated, especially with regard to undesirable graphite morphologies. A particular and important development has been the austempered spheroidal graphite cast irons with increased strength owing to the transformation of the matrix to upper or lower high carbon bainite, from the 1980s onwards. Alloy white cast irons were developed during the period up to 1950s, for example Mo and Cr irons have been used since before 1940 for increased wear and abrasion resistance, and for corrosion resistance. There were then developed the high Ni-Si irons, which with an austenitic matrix were first introduced in the 1930s and have been replaced by the modern corrosion resistant irons with up to 30%Ni and 5%Si. High Cr irons, containing 30%Cr and up to 2%C, combined corrosion, heat and abrasion resistance. Added to these were the high Si irons and aluminium irons containing up to 7%Al or even 20%Al for oxidation resistance. Irons with martensitic matrices such as Ni–Cr, Ni-hard irons and the austenitic matrix Ni-resist iron containing up to 3%Ni with ~ 3%Cr, were then developed. These developments, which cannot be detailed here, have resulted in the family of cast irons becoming very sophisticated materials.
19.11 Closing Comments

From the foregoing which can only give an overall impression of the more significant steel developments in the twentieth century, it can be appreciated that these have been immense. They accelerated markedly after about 1950 with the development of metallurgical understanding brought about by the new and powerful techniques for examining microstructure, reaching a peak by perhaps the 1970s and thereafter decline as more emphasis was placed on process developments and steel quality control. The need has continually increased for more combinations of properties to be possessed by a given material, and for much more stringent conditions of use to be met. Not all the developments reached full commercial potential, although many did, and some were ephemeral in that they were rapidly replaced by other developments. It cannot be in doubt that at the end of the twentieth century steel is perhaps the most sophisticated engineering material of all time.

The most recent developments, not in steel compositions but in the uses of steel, to determine the compositions required, have spawned the many materials optimiser systems and dedicated expert systems. Whilst being of considerable use in more simple alloy design and selection, they must not be regarded too seriously as the siren voices whose calls can replace detailed knowledge and thought. So complex are the interactions of the variables in steel behaviour that, even at the end of the twentieth century and no doubt well into the future, they will not be able to replace fully the vast library on, and comprehensive understanding of, the most unique of engineering materials - steel.

20. CLOSURE

At the start of the twentieth century the iron and steel industry was largely a craft and indeed in many areas something of an art. Although based on centuries of tradition, at least in terms of ironmaking, by modern standards the production units were relatively small scale and could not be described as mass production. The manufacture was disseminated and the introduction of a sound scientific base, and consequent understanding, was as yet in its infancy.

During the twentieth century, as indicated by the technological developments outlined, which have by no means been exhaustively or comprehensively described, the industry, particularly the steel industry, had become fundamentally science based and moved truly into the stage of mass production. Apart from a natural product such as wood, and aggregate such as concrete, steel is by far the predominant engineering material, and is likely to remain so for the foreseeable future. Never has a mass produced material been made and processed by such a range of sophisticated methods. Never has a material produced in the hundreds of million tonnes a year, enjoyed such a scientifically underpinned base. The understanding of the mechanisms underlying its manufacture and use is at a level inconceivable in 1900. Many innovations and developments have been made in the types of steel produced, all now based on sound scientific principles, and the factors con-
trolling the microstructures of those steels and their properties and potential in use are, to a large measure, clearly understood. In addition, the modern iron and steel metallurgist has at his disposal a range of investigational techniques that are capable of studying steel at the atomic level of resolution, making understanding uniquely comprehensive. In fact it is hard to see how much further these investigational techniques can be pushed to achieve further developments. So successful has the metallurgist been, that he now has the ability to produce properties in steel which exceed most of the demands imposed by engineers. This must not be viewed complacently, as the requirements of economics place ever greater challenges, especially in terms of quality standards.

The greatest rate of innovation in steel manufacture, processing and in the development of new and improved steels with superior properties occurred in the period 1950–1980. At this time, steel companies were committed to research and many research organisations were established. Not surprisingly, this was also the period of the most intense investigational techniques innovation. In retrospect, it might be concluded that too much attention was paid to this aspect, particularly the arguably excessive sophistication of technique which syphoned off much high calibre metallurgical manpower away from essentially metallurgical work. It was the heyday of physical metallurgy and, not surprisingly, a reaction set in. Even from the early 1970s, and some years earlier, there were fluctuations in demand for steel and the rate of world production slowed (Fig. 1) but not too dramatically. After 1980, however, the rate of increase of world steel production markedly decelerated. The reaction largely took the form of increased attention being paid to process metallurgy, and the economic advantages that could be achieved from computer control and automation of processes. Research organisations began to decline in size and importance and even to close. Attention then, and later towards the end of the twentieth century, has turned to quality control, the development of systems approaches, and the decrease in the basic research which had supported the massive increase in steel usage during the boom years. This is continuing today as high calibre metallurgical manpower becomes ever more involved in 'fire fighting', urgent problem solving taking precedence over long term interest in metallurgical developments. In part this accounts for the seemingly lack of technical innovation, and especially in the development of concepts, over the last two decades. The question must be asked as to whether stagnation has set in similar to that experienced in physics at the end of the nineteenth century or in the geological sciences before the concept of plate tectonics. The time is probably overdue for another series of metallurgical advances, but it is difficult to predict just where and how this will occur.

It is probably premature to write off steel as an obsolete engineering material. Its advantages were discussed in the Introduction and these are so potent that, coupled with the requirements of an ever increasing world population, the demand will doubtless increase slowly in the future. Where will future developments occur? Already potential properties exceed many demands, and so new and improved steels are less likely, especially as their development is hindered by the
move away from the fundamental research on which they are based. Also, as will be returned to later, there is a lack of high calibre metallurgists to bring about such developments. Perhaps the seed corn has been consumed in the interests of economics.

Will there be dramatic developments of new processes? Many existing processes have a long history, the blast furnace being an example. At the end of the twentieth century basic oxygen and electric arc steelmaking are predominant together with many secondary (ladle) steelmaking processes. Direct reduced iron may replace blast furnace iron, possibly completely. Bearing in mind the compelling needs for conservation, the higher scrap usage in electric steelmaking (50%) may well favour it over basic oxygen steelmaking (30% scrap). There may therefore be a move towards continuous production from ore to the liquid steel, with the final finishing of the many different compositions being accomplished in secondary steelmaking vessels. Continuous casting with direct rolling could then complete the operations, and thin slab casting could increase the proportion of sheet and strip material produced, as this latter is already processed by continuous methods. But there is a huge capital investment in existing plant, which will act as a brake on spectacular new process developments.

Steel refining techniques are already capable of producing such low impurity levels that they are difficult to quantify analytically. This trend will probably continue, challenging the special steelmaking processes such as electroslag and vacuum arc refining. The development of specific detectors for continuous analysis of the liquid metal is likely to materialise in the next century, so that the processes could become fully automated. The basic principles for the control of a substantially continuous process are already understood, but their application will not be simple, although the modelling of such a system is well advanced, particularly in the area of hot working for microstructural control. No doubt there will have to be changes in existing processing routes to accommodate the changes in liquid metal practices, casting procedures, and also impurity levels, and especially to produce the crystallographically textured sheet and strip for formability.

Surface engineering is also a very logical development as many steel uses are surface dependent rather than requiring through section properties. It is reasonable to expect an expanding application of the many techniques of surface engineering in the twenty-first century. But the most important part of any organisation is the people engaged in it. It must be remembered that the period 1950–1980 coincided with the ideological conflict of the Cold War. This led to a reaction against science and the political-industrial hegemony which was then apparent. Fewer students opted to study science and technology and nowhere was this more so than in metallurgy, especially as the problems of over-production, steel plant closures, rationalisation and manpower redundancy became apparent to potential young technologists. The steel industry had a bad ‘press’ and teaching organisations found difficulty in filling courses and so attempted to maintain viability by changing to materials studies. Metals, and steels in particular, formed an ever decreasing part of the curriculum. The supply of high calibre metallurgists to the industry
declined. In addition a most marked trend over the last 30–40 years has been a more generalised education. Whilst acclaimed by many academics, often not of a technological predisposition, the steel industry faced a further recruitment problem which to some extent was self-imposed because of its desire for graduates to have a rounded knowledge of management, economics, accountancy and marketing, as well as metallurgy. A further adulteration of the metallurgy content of courses occurred with the introduction of combined degrees, e.g. materials/management etc. Whilst such a rounded knowledge is important in the wider and higher management positions, the result has been a further decrease in the supply of specialist metallurgical manpower who are absolutely essential to a science based industry. Such specialist knowledge has tended to be acquired by post graduate courses which, despite the increasing total numbers of graduates, have not been able to make up the deficit.

Appreciating this, the steel industries of much of the western world moved further away from research and more into optimising the economics of production. There were also challenges from competitive alternative materials. A downward spiral was inevitable. Steel became considered a material of the past and much more excitement was generated by the ‘sunrise’ materials and technologies, largely because of adverse publicity from the media and the absence of active encouragement from governments, who failed to appreciate the need for a manufacturing base in order to pay for the imports required by UK plc. This cannot be provided entirely by the service sector of the economy and there is a further danger of a downward spiral if too large a portion of the productive manufacturing base is eroded by ‘short-termism’.

A further feature of the past 30–40 years is that degree students have become more selective in the types of course they follow. This has been partly owing to the perceived rewards in the various professions. Engineering and scientific disciplines, especially in industry, have lost out to medicine, law, accountancy, economics and even media studies, and have failed to attract the more capable students. Maybe it will be necessary to provide incentives, possibly in the form of scholarships to students reading the industrial technologies, including metallurgy. Alternatively it will be necessary to ensure that the supply of high calibre scientific and technological manpower is encouraged to match the national requirements.

The UK steel industry operates in an internationally competitive environment and is now as efficient as any in the world judged by steelmaking performance and quality. This, however, does not guarantee future viability as some of the competitors have in-built advantages in terms of cheap labour, government subsidies and freedom from health, safety and environmental restrictions. In these conditions, the present competitive position of the UK iron and steel industry has only been achieved by hardship consequent upon the rationalisation of production facilities and a 70% reduction in manpower since the 1960s. This could not have been achieved without the basic knowledge and understanding of steel and its processing, consequent upon a highly trained and skilled scientific workforce and its metallurgical knowledge. It has ensured survival and has fought off the many
challenges from competitors and alternative materials. The same requirements are likely to be even more necessary in the twenty-first century.

We should not, however, consider the year 2000 to be a defining moment when all changes. Rather it is just part of a continuum of change and development which this review has charted. Often the changes have comprised individual small accumulative improvements rather than massive leaps. No doubt this will continue into the twenty-first century and indeed is the most likely scenario. The steel industry and steel itself has been rather denigrated in the last twenty years or so, and this is nothing new. But it does lead to some loss of confidence and people involved in the industry must not lose faith in the viability of this pre-eminent engineering material. The steel industry has risen to challenges in the past and no doubt will do so again successfully. But we must not delude ourselves in thinking the changes required, indeed which are essential, will be easy.

21. BIBLIOGRAPHY

In order to provide even a reasonably exhaustive list of references, covering all the innovations and developments that have been referred to in the above review, this would run into possibly thousands of items, and be quite impracticable in a work which has an historical broad sweep. Consequently the authors have selected a number of books which they consider will provide background reading for the developments that have occurred in the twentieth century.

Selection of such works in an invidious task, and the list is by no means comprehensive. Rather than give many individual papers, textbooks of a more or less didactic nature have been chosen, together with some proceedings of various conferences which contain either useful reviews or as a whole mark a distinct stage in development.


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CHAPTER 3
The Iron and Steel Institute

C. Bodsworth

1. EARLY DEVELOPMENTS

The Iron and Steel Institute was inaugurated in 1869 and for 104 years it played a leading role in the development of the ferrous industries in Britain. It ceased to exist as a separate entity in 1973 when it participated in the first of a series of mergers that culminated in the formation of the present Institute of Materials. Through publications, meetings, conferences and visits to metallurgical centres in Britain and overseas, it facilitated the continuing professional development of its members long before that phraseology was promulgated as an objective for a professional organisation. Two accounts describing some of the activities undertaken by the Institute were written up to commemorate its centenary\(^1,2\) and a further report was published\(^3\) to mark its demise.

Most manufacturing operations were shrouded in secrecy in the eighteenth century, but the ironmasters eventually began to realise that advantages could arise if they met in groups to discuss matters of common interest. The debates were limited initially to consideration of the economic aspects of the industry. Meetings were arranged, for example, to seek agreement on selling prices for their products, or to restrict production and maintain prices during periods of economic depression. The ironmasters in the Midlands met frequently during the times of the Napoleonic wars and the practice was soon copied by other districts. A severe recession which occurred in the late 1830s prompted these various groups to get together in an attempt to control the total production and to stimulate demand.\(^4\) But the co-operation was desultory and largely disintegrated when prosperity returned.

As the industry entered a period of rapid expansion in the middle years of the nineteenth century, a need began to be recognised for more wide ranging discussions at which information on practical and technical matters could be exchanged and debated. Various local associations were formed for this purpose, including the South Wales Institution of Engineers (founded in 1857), the Cleveland Institution of Engineers (1864) and the Staffordshire Iron and Steel Institute (1867). The Engineer and the Iron and Coal Trades Review journals also brought detailed information about developments in practices and processes to a wider audience. But the industry was slow to develop a means of bringing together practitioners from all the ironmaking districts to discuss problems and possible sol-
utions on a national basis. Members of other disciplines had adopted the practices developed by the Royal Society as a basis and set up professional bodies, such as the Institute of Civil Engineering (1818) and the Institute of Mechanical Engineering (1847), while the British Association (1834) served a wider audience. Members of the iron and steel trades had to address meetings arranged by these Societies when they wished to bring their work to a wider audience. Thus, Henry Bessemer’s first account of the invention of the converter process was presented at the 1856 meeting of the British Association. His subsequent paper, which described the development of the process into a commercially successful operation, was read at a meeting of the Institute of Civil Engineers in May 1859.

Seeking to redress this situation, a meeting was called by the North of England Iron Manufacturers Association (NEIMA) and held on 28 September 1868 at Newcastle-upon-Tyne. A proposal to form an Iron and Steel Institute was tabled at the event by John Jones, the Editor of Iron and Coal Trades Review and secretary of NEIMA. It received an enthusiastic reception and a provisional committee comprising Henry Bessemer, Isaac Lowthian Bell, John Jones and representatives from the principal iron and steel manufacturing districts was set up to develop the concept and investigate the probable success of such a venture. The committee found strong national support and, accordingly, a meeting was held on 17 December 1868 at the Westminster Palace hotel at which Mr I. Lowthian Bell presided. The initial rules for the Institute were drawn up and it was resolved that William Cavendish, the 7th Duke of Devonshire, chancellor of Cambridge University and chairman of the Barrow Hematite Steel Company, should be invited to take the chair as the first President.

The first general meeting was held in London on 25 February 1869 and the Duke delivered the first Presidential Address on 23 June at a meeting held in the Hall of the Royal Society of Arts. In his address he commented that

> it must be a matter of some surprise that an Institution of some kind has not been long ago called into existence. The importance is all the more manifest when we bear in mind the progress which other countries have recently been making in this branch of industry.

He continued with a definition of the role of the new body with the statement that

> This Institute will afford facilities for imparting to its members the knowledge of any valuable discoveries, whether scientific or practical, originating abroad, and of any contributions bearing on the metallurgy of iron which may make their appearance in continental publications.

Thus, from the outset, the Institute was constituted to consider both the practical and the theoretical aspects of the manufacture and use of iron and steel. It was required to take a non-parochial stance, but “exclude all questions connected with wages and trade regulations” and arrange communication between the members by meetings and publications.
Since one of the primary objectives was to encourage open and frank discussion of matters of common interest, without hindrance from restrictions imposed by ‘secret’ operations, it was decided that membership should be open only to individuals and not to industrial organisations. Accordingly, 292 members were elected in the first year, most of whom were proprietors or senior managers of iron and steel works and all had obtained knowledge of the industry solely from practical experience. They dominated the development of the industry during the next two decades. The first overseas member, Mr T. Blair from Pittsburgh, USA, was also elected. The membership fee was set at two guineas (£2.10). John Jones was appointed as the first Secretary, but he continued also with his other editorial and secretarial appointments.

Under the guidance of William Cavendish, the Institute began to publish an annual volume of Transactions but, from 1871, the title was changed to the Journal of the Iron and Steel Institute (referred to hereafter as the Journal of the Institute) and normally two volumes were issued in each year. The first tentative steps were taken to initiate and co-ordinate collaborative research projects when two research committees were set up in 1870. One of these, under the chairmanship of William Menelaus, collected and evaluated information concerning the methods available for the mechanical puddling of iron. As described in Chapter 2, a delegation was sent to the USA to evaluate and report on the Danks’ mechanical puddling furnace. The second committee reported on the distribution and composition of the British iron ore deposits. It was unfortunate in this context that whilst the report on mechanical puddling aroused considerable interest, the concept was soon rejected by the industry as economically unattractive and Spain soon became a major source for the hematite ores used for smelting in Britain. This is perhaps the principle reason why the Institute mounted no further collaborative research ventures until 1917. When, in the late 1880s, some members collaborated in an Alloy Research Committee, the reports were presented to the Institute of Mechanical Engineers.

By the end of the first Presidency, in 1871, the aims and objectives of the Institute were well recognised and the _modus operandi_ was firmly established. This continued with surprisingly little change well into the twentieth century. In recognition of his guidance through the critical stages of the establishment of the Institute, the Council arranged for a portrait of the Duke to be painted (Fig. 1). This has been on continuous display by the Institute and its successors. It can now be seen in the entrance hall of the premises of the Institute of Materials at 1 Carlton House Terrace in London.

Sir Henry Bessemer was elected as the second President, to hold office for two years. This became the standard term of office until 1917, when the practice was changed to elect a new President each year. The membership had more than doubled by the end of Bessemer’s appointment, with 137 members resident overseas, and it was approaching 1000 members by the end of the first decade of its existence. The London offices of the Institute in Victoria Street provided barely sufficient accommodation for small committee meetings and larger gatherings had to be accommodated elsewhere. The practice soon evolved of
holding the spring general meeting each year in rented accommodation in London.

The autumn meeting was usually located in one of the regional iron and steel manufacturing centres, where the delegates were invited also to tour the local works, whilst the ladies enjoyed a programme of cultural visits. This procedure was followed for many years. Detailed accounts of the speeches and visits were published in the Journal of the Institute. These make interesting and sometimes amusing reading. For example, the report of the meeting held in Sheffield in 1905 describes a visit made by delegates to Chatsworth House, the home of the Duke of Devonshire. It describes how

_{Seventy-three conveyances had been chartered for the occasion, of which twenty were coaches holding 20 passengers each, and the remainder pair-horse landaus. The start was made from the Cutlers Hall at 9 a.m., and the whole party was well under way by 10 a.m. The weather was unpropitious and heavy rain fell on the (10-mile) journey between the city and Chatsworth._

The first coaches arrived at the destination by 12 p.m., but the passengers on the last to arrive missed the tour of the house and were taken straight to lunch. (It was
appropriate that the delegates to the Bessemer centenary conference held in Sheffield in June 1998 were also entertained to dinner at Chatsworth. Travelling by motor coaches, they all arrived together after a half-hour journey.

In furtherance of the objective to provide members with information about the ferrous industries in other countries, Bessemer led a contingent to attend technical sessions and visit works at Liege in 1873. Overseas meetings followed in Paris (1878), Dusseldorf (1880), Vienna (1882) and Paris again in 1889. Meetings were also held in New York in 1890 and again in 1904. Reports of these visits were also published in the Journal of the Institute, or occasionally as a special edition. Overseas meetings then diminished in frequency for a time, but from 1953 to 1965 they were an annual event. A total of thirty-seven meetings were held in other countries under the aegis of the Iron and Steel Institute.

Bessemer donated to the Institute a large collection of samples of steel made during the development of the converter process, together with medals that had been presented to him and other artifacts. Some of these are still stored at the Carlton House premises. The scroll admitting him as a Freeman of the City of London was presented to him in a magnificent golden casket, on top of which is a figure depicting Commerce standing between a model of a Bessemer converter and a stack of ingots (Fig. 2). The casket is now on display, together with folios of his engineering drawings, in the Bessemer room at the Institute. He provided an endowment to finance the annual award of the Bessemer medal to recognise an outstanding contribution by the recipient to the ferrous industries. The first medal was awarded to Sir Lowthian Bell, the third President of the Institute, who had written up his pioneering work on the development of the blast furnace process in a series of papers which dominated the early volumes of the Journal of the Institute. In the following year, the medal was presented to C. W. Siemens, the inventor of the regenerative furnace. The list of the subsequent metallurgical recipients could be regarded as an international 'who's who' of the leading contributors to the industry. The medal is still presented annually as the premier award of the Institute of Materials. Subsequent benefactors endowed other medals and awards, including the Andrew Carnegie gold medal (awarded 1902–1946) and silver medal (1903–1966), the Sir Robert Hatfield medal (from 1947) and the Williams prize (from 1927).

All papers accepted for publication during the early years of the Institute were read at one of the general meetings and were then printed in the Journal of the Institute with a verbatim report of the discussion. Most of the early papers were concerned with the manufacture of iron and steel. Few considered specifically the production of castings, mechanical working processes or the properties of the wrought metal. As the years progressed there were more frequent accounts of empirical investigations undertaken to improve productivity and to reduce the rate of rejection but, by modern standards, they were very limited in both scope and depth. As Niall Campbell Macdiarmid remarked in his Presidential address to the Centenary meeting
Their technical content was in keeping with the current and limited scientific knowledge. ... A wide gap existed between the leading figures who were evolving and codifying the practical and scientific aspects of iron and steel making and the ordinary member of the Institute who had had, as then, little opportunity to see the new heights or understand their prospects.  

Perusal of those papers can be a profitable pastime, however, for reinterpretation of the data in the light of present knowledge can lead to some useful indicators for further work.

Fuel economy was a recurring topic, for projections forward of the amount of coal, which would be required to satisfy the continuously rising demand for iron and steel production, were interpreted as evidence that the coal reserves would soon be exhausted. (This theme of an impending fuel shortage seems to have been repeated at regular intervals during the following century). Many papers were concerned with optimising both the size of the blast furnace and the hot blast temperature to reduce coke consumption per ton of iron, or with the application of waste heat boilers and similar topics. But scattered among these relatively mundane papers were some which proposed very significant advances in production methods, including thin strip casting, direct reduction, the two-electrode electric arc furnace and vacuum treatment of molten metal. Economic restrictions and the limited engineering knowledge prevented the immediate development of most of these proposals and over a century was to pass before they had all achieved commercial success.
Inspection of those early volumes of the journal reveals that the discussion of the papers at the meetings was dominated by a relatively small number of the leading members of the profession. It reveals also that almost half of each volume was devoted to extended abstracts of relevant papers that had been published elsewhere in Britain and overseas, together with detailed reports and evaluations by the secretary of new developments. A comprehensive coverage was provided of statistical data for the production of coal, iron ore, cast iron, wrought iron and steel for every country with a significant manufacturing base and details of exports from and imports to the United Kingdom. In pursuance of the worldwide objective defined by the first President, David Forbes had been appointed in 1871 as the Foreign Secretary to co-ordinate the reports for overseas countries. The statistical data for British industry was taken mainly from information published in *Iron and Coal Trades Review*, in the compilation of which, wearing one of his other hats, the Secretary had presumably been involved. These were all published under the heading 'Notes on the progress of the home and foreign iron and steel industries'.

John Jones, who had played a leading role in the creation of the Institute, died in 1877. As Secretary of the Institute he had been primarily responsible for the production of the Journal of the Institute and the immediate success of the general meetings was a tribute to his organising ability. He was succeeded as Secretary by James Stephen Jeans, who wrote several books about the industry and about its personalities during his term of office. He also contributed technical papers at the general meetings, including a reasoned argument for the expansion of technical education. Under his guidance, a library was opened in 1881 when the offices were moved into more spacious accommodation at Victoria Mansions, Victoria Street, London. The library was funded initially by a surplus of £112 remaining after the costs of the London meeting in 1881 had been met from the fees charged to participants.

Jeans resigned his post in 1903 when he became the editor and acquired a controlling interest in *Iron and Coal Trades Review*. B. H. Brough then filled the post of Secretary until 1908, followed by G. C. Lloyd until 1933 and then by Kenneth A. S. Morley. Anthony J. Post was the incumbent from Morley's retirement in 1967 until the first of the mergers occurred in 1974.

The dominance in the Journal of the Institute of papers describing the manufacturing processes gradually declined during the first three decades of the life of the Institute. Initially the only papers of a technical nature had a chemical orientation, providing accounts of investigations, such as attempts to define the sequence and extent of the chemical reactions that occurred during extraction or refining operations, or the analysis by spectrographic methods of the gases produced in the refining processes. Papers describing methods for the chemical analysis of metals, ores and slags were not normally published in the journal, but one section of the literature reviews contained brief accounts of new procedures. With increasing frequency, however, the chemical compositions of the metals under consideration were quoted in the papers. The reproducibility of the analyses was generally rather poor, but the concentrations of elements present in iron and steel were invariably quoted to three decimal places.
A slow start to the introduction of other technological topics was made in 1879 when a Swedish professor, R. Akerman, presented a paper on the hardenability of steel. Within the next two decades Sorby, Osmond, Arnold, Carpenter and others began to present papers on the new discipline of metallography and a start was made to cover structure-property relations, which led in turn to the study of alloy steels. A total of 686 papers and 2309 abstracts had been published in the journal by 1904. The vast majority of these papers were practically oriented but the balance had changed and about one third were of a technical nature by the start of the twentieth century.

Evidence that the Institute was widely recognised in other countries by this time is provided by the number of overseas members, which had increased to 20 per cent of the total, and most volumes of the journal now contained one or two papers that had been submitted by authors resident overseas. The status was recognised in 1899 by the grant of a Royal Charter, which was presented as a gift from the President, Sir Hughes Bell. Queen Victoria accepted the award of the Bessemer medal in the Charter year. A new category of Honorary Member had been created in 1888 and the first person admitted to the grade was HRH Albert Edward, Prince of Wales. Following his ascension to the throne, he became the first Patron of the Institute. The succeeding monarchs have also been Patrons throughout their reigns. The Bessemer medal was accepted by King Edward VII in 1906, by King George V in 1934 and by Queen Elizabeth II in the Centenary year. The list of past Honorary Members includes King Leopold, King Albert, King Leopold III and King Baudoin of Belgium, King Oscar II of Sweden and Norway, Grand Duchess Charlotte of Luxembourg, Archduke Friedrich of Austria and President Masayk of the Czechoslovak Republic.

A coat of arms and the motto Faber, Fabrum, Adjutet was granted to the Institute in 1908. It depicts a stag’s head, representing the emblem of the first President, the 7th Duke of Devonshire, and two Hawks bells, commemorating Sir Lowthian Bell the third President, on a black background and beneath the symbol for Mars, the alchemic symbol for iron (Fig. 3). This adorned all subsequent publications issued by the Iron and Steel Institute.

Andrew Carnegie, one of the pioneers of the iron and steel industry in the USA, presented a cheque for £13,000 to the Institute in 1900 to finance a scheme for the award of grants to encourage students of metallurgy ‘to conduct researches in the metallurgy of iron and steel and allied subjects, with the view of aiding its advance or its application to industry’. Recipients of the Carnegie Scholarships were required to submit a written report on the completion of their studies. These were published initially in the journal, but from 1904 onwards they were issued annually under separate cover entitled Carnegie Scholarship Memoirs. The scheme was highly regarded, with keen competition for the awards, so Carnegie gave a second cheque for £13,000 in 1908 to top up the fund. These donations were invested and the amount used to fund the Scholarships was limited to not more than the annual income to ensure that the value of the fund was maintained. This was not normal practice at that time, but the policy was so successful that by 1920 the assets of the
A fairly close collaboration had evolved with other engineering institutions. The annual London meeting was usually held in the premises of the Institute of Civil Engineering and this arrangement continued until 1939. A more formal association developed in 1901 when the Iron and Steel Institute, together with the Institutions of Civil and Mechanical Engineering and the Institute of Naval Architects collaborated in the formation of the Engineering Standards Committee and the International Association for Testing Materials. The first of these bodies subsequently developed into the British Standards Institution.

The number of members fell slightly during the recession, which lasted from 1891 to 1896, but then increased slowly to reach 2200 by 1909. The growth was then checked once again and began to fall when members were called to the colours for service during the 1914–1918 war. The total membership remained fairly constant
throughout the depression which persisted in the 1920s and only began to increase significantly above the 2000 mark from 1936. The number of members resident overseas continued to increase, however, rising to 25 per cent of the total in 1910. After a temporary check during the war years, the proportion from overseas increased to 33 per cent in 1930.

The Iron and Steel Institute had continuously declined to accept all proposals to establish regional centres but, in an effort to increase the membership during the war years, the Cleveland Institution of Engineers, the Sheffield Society of Engineers and Metallurgists, the Staffordshire Iron and Steel Institute and the West of Scotland Iron and Steel Institute were recognised as Affiliated Societies. The grade of Associate Member was introduced in 1917 for joint membership with one or more of the above bodies. This proved to be a popular development and the list of Affiliated Societies increased steadily thereafter, reaching a total of 17 by 1960. The Institute provided a small annual grant to help with the running cost of each of the Societies and their Presidents served as members of Council.

2. CO-OPERATIVE RESEARCH

Few works employed a chemist to analyse materials at the time when the Iron and Steel Institute was created. As time progressed, however, and the volume of technical literature pertinent to the industry increased, the leading companies set up analytical laboratories and mechanical test houses. The first metallographic departments within the works began to appear soon after the turn of the century. All the leading companies had established research departments by 1914 but, in marked contrast, many of the smaller companies had made negligible progress in this direction and could make only limited use of new knowledge.

The demand for increased production with closer tolerances for products to meet the needs of the armed forces at the outbreak of the First World War quickly led to a recognition of the need for a greater interchange of information. The Institute took a leading role in persuading the more efficient companies to allow wider access to expertise and to collaborate in a joint effort to improve the productivity and quality standards of the less efficient manufacturers. Knowledge increased rapidly and overall productivity increased, but this served primarily to draw attention to the disparate standards of performance which still existed across the country. Capitalising on the mood for closer inter-company collaboration, therefore, the Council of the Iron and Steel Institute set up five research committees in 1917. These were named: No. 1, Iron Ore, Fuels and Refractories; No. 2, Blast Furnace Practice; No. 3, Steel and its Mechanical Treatment; No. 4, Iron and Steel Foundry Practice and No. 5, Metallography, Chemistry and Physics. Each committee started out by circulating questionnaires designed to elucidate information from which could be deduced the best current practice pertinent to specific issues of general concern. Some investigative work was undertaken in individual laboratories, but no co-operative research involving more than one company had been started before peace was restored in 1918.
The marked fall which ensued in the demand for ferrous products and the sharp decrease in the profitability of the manufacturing operations resulted in the cessation by 1921 of all the activities covered by the first four of the research committees. The more fundamental studies, which had been started by the metallography group, were considered necessary to broaden the scientific base of the industry and Committee No. 5 continued to meet until the Diamond Jubilee year in 1929. Its first major accomplishment was the preparation, in collaboration with the National Physical Laboratory, of standard specimens of iron and steel for the calibration of chemical analyses. The difficulties that were encountered in obtaining adequate quantities of homogeneous metal for the standards drew renewed attention to the occurrence of segregation during solidification. Accordingly, a Committee on the Heterogeneity of Steel Ingots was set up by the Institute to investigate this issue. It met for the first time on 20 November 1924 under the chairmanship of Dr W. H. Hatfield, Director of the Brown-Firth Research Laboratory. This was the first truly co-operative research activity, which was supported unanimously across the industry. During the next two decades a systematic study was undertaken in which more than seventy ingots in a wide range of sizes and compositions were sectioned and macroscopic and compositional variations were meticulously recorded. The first three reports produced by the Committee were published in the Journal of the Institute, but six subsequent reports and several supplementary accounts were reproduced under separate covers as Special Reports.

The enthusiastic reception of the early reports on heterogeneity encouraged the Institute to form a Technical Committee. This was created in 1927 with four new co-operative groups: No. 1, Coke-Oven Plant and Practice; No. 2, Blast Furnace Plant and Practice; No. 3, Steel Furnace Plant and Ingot Production and No. 4, Rolling Mill Plant and Practice.

The National Federation of Iron and Steel Manufacturers came into existence in 1918 (changing its title to the British Iron and Steel Federation in 1934). The Iron and Steel Industrial Research Council was formed in 1929 as a joint committee of the Federation with the Institute, the government’s Department of Scientific and Industrial Research and other interested bodies. The responsibility for the organisation and the funding of the Research Committees was then passed from the Institute to the Research Council, although the Institute continued to provide library and secretarial services for the Joint Research Committees. The Heterogeneity of Steel Ingots Committee, which had been formed initially as a sub-committee of the wartime Metallography Committee, now achieved full status and the Metallography group was disbanded. The four new groups, which had been formed two years earlier at the Institute, were reconstituted as new committees between 1930 and 1932. New committees were also formed to co-ordinate studies of corrosion (1928), steel castings (1930) and alloy steels (1934). Each of these in turn sponsored sub-committees charged with specific tasks. For example, the Liquid Steel Temperatures group designed the first reliable rapid immersion thermocouple, whilst others examined diverse topics such as thermal treatments, inclusions, gases in metals and hairline cracks. As Secretary of the Institute, Mr K. A. S.
Headlam Morley served also as secretary of the four main research committees and as a member of the other committees and sub-committees. All the reports emanating from the groups were published either in the Journal of the Institute or as Special Reports. The DSIR paid a subvention to the Institute to defray part of the costs incurred.

A detailed account of the development of the co-operative research activities was produced as Special Report No. 29. It is evident from this report that an increasing strain was being placed upon the laboratories of the companies who were collaborating most actively in the investigations. By the early 1940s a need had been identified for the creation of dedicated laboratories staffed with specialists, who could conduct the investigations free from the pressures and constraints imposed by close association with production departments. The British Iron and Steel Research Association (BISRA) was formed accordingly in 1944 and took over the work of the joint committees. The important role that the Iron and Steel Institute had played, however, in the development of co-operative research activities was recognised by giving the Institute's Council the authority to appoint several members of the BISRA Council. The Institute continued to provide library facilities for the new body and an information officer was appointed to answer queries from the members and the BISRA staff. Papers produced by the staff of BISRA were published under a separate heading in the Journal of the Institute. Dr Hatfield, who had served as chairman of the Technical, Heterogeneity and Corrosion committees, took a leading role in the preparation of Special Report 29. He died shortly after it was completed, but the Hatfield Memorial Lecture, which has been given annually since 1946, perpetuates his memory.

3. GROSVENOR GARDENS HEADQUARTERS

The long period of negligible growth of the ferrous industries, which had started in 1920, came to an end in the mid 1930s and the number of people employed in the industry increased in line with the increase in total production. The increased profits then generated enabled companies to expand their research and development departments to participate in, and make use of the data from the co-operative research committees. These changes brought about a sudden increase in applications to join the Institute and the membership increased by 40 per cent between 1935 and 1939.

The offices of the Institute, which were still located in Victoria Mansions, had proved barely adequate to accommodate all the services required by the joint research committees and could not meet the requirements imposed by the surge in membership numbers. The problem was resolved when several of the leading companies in the industry joined together to purchase a 15 year lease on a large terrace house at 4 Grosvenor Gardens (Fig. 4) and when this expired in 1953 a further lease for 60 years was purchased by the same donors. The offices of the Institute were transferred to the new accommodation in 1938. After the provision of a large
council chamber, a spacious library and several committee rooms, there was still more office space available than would be required in the foreseeable future. Accordingly, the Institute of Metals, which had been formed in 1908, was invited to share the use of the new premises in return for a contribution towards the running costs. The libraries founded by the two bodies were amalgamated into a Joint Library.

A significant portion of the office space was occupied by the publishing activities, which had also grown rapidly. The number of papers submitted for publication had increased steadily from the resumption of the co-operative research activities and by the late 1930s a stage had been reached where they could not readily be accommodated in the two case bound annual volumes that were distributed.

Fig. 4 Registered Office of the Iron and Steel Institute, 1938–1972, at 4 Grosvenor Gardens, London.
to members. The costs of publishing had also increased and, although the annual membership fees had been increased, the production of the publications was absorbing a progressively larger slice of the income. Plans were formulated, therefore, to change to a monthly journal from January 1940, which would be partially self-financing through the incorporation of paid advertisements in each issue. The outbreak of the Second World War in 1939 interrupted the planned schedule and the periodic issue of separate preprints of the papers, subsequently incorporated in two bound volumes, continued during the war years.

After a slight check to the growth in 1940, the membership increased rapidly during the war and exceeded 4000 by 1945. This helped to restore the financial solvency of the Institute, for it had had to appeal for donations from industry to sustain its activities during the early 1940s. (This also explains why the author on arriving at work one day was presented with a completed membership form for his signature and informed that the company would pay for his first year of membership of the Institute!)

The change to a monthly journal was finally introduced in 1947 and the revenue received from the advertisements soon transformed the financial situation. Each issue of the Journal contained a final section entitled 'Abstracts of Current Literature and Book Notices', followed by 'News From Industry', maintaining the arrangement introduced in the first issues of the annual journals by J. Jones and D. Forbes.

The trend towards a more fundamental study of metallurgical operations and the growth of company research laboratories resulted in a marked growth from the late 1930s onwards in the number of personnel employed in the industry who held post-school qualifications. The majority of these people had studied pure science disciplines and relatively few held qualifications in metallurgy. Towards the end of the 1939–1945 war, when thoughts were turning to what the manpower requirements would be when peace had been restored, some leading members of the profession led by William E. Ballard initiated debate on the need for a formal qualification procedure. After extensive discussions and correspondence, a meeting was organised by the Birmingham Metallurgical Society and the Staffordshire Iron and Steel Institute. A resolution was passed at the meeting requesting the Councils of the Iron and Steel Institute and the Institute of Metals either to set up a qualification procedure administered by the Institutes, or to create a new body to undertake the task.

The Institutes were not prepared to accept the burden of monitoring qualifications and eventually agreed to develop the alternative request. The Institution of Metallurgists was set up accordingly on 15 September 1945. It was charged with the task of devising and monitoring a suitable package of education and experience, which would lead to professional status in the metallurgical discipline, but was precluded from any publishing activities which might overlap with the territories of the two parent Institutes. The Secretary of the Iron and Steel Institute, K. A. S. Headlam Morley, was appointed Secretary of the Institution of Metallurgists as well for 1945–1946. The Registered Office was accommodated at 4 Grosvenor Gardens until the Institute moved to other premises in 1953.
The proportion of papers appearing in the journal that were written by scientists and concerned with the metallurgical control of process operations, structure–property relations and a wide range of other specialised topics had increased rapidly during the war years. Few papers were now published dealing with the design and maintenance of production plant and only occasional contributions dealt with the mechanical working of iron and steel. In an attempt to redress the balance the Iron and Steel Institute formed an Iron and Steel Engineers Group in 1946, with a separate co-ordinating committee and calendar of events.

The wide spread of more specialised topics addressed in the journal made it increasingly more difficult to select a group of papers to form the basis for a discussion at the annual general assemblies. From time to time the Institute had organised meetings on specific topics at which invited papers were presented and discussed. The proceedings were then published as Symposia, typical of which are the reports on Welding (1935), Steelmaking (1938), Powder Metallurgy (1946) and Hardenability of Steel (1946). Now the Council turned increasingly to the organisation of conferences, where the proceedings were published as a special report. From the late 1950s relatively little space in the journal was devoted to the written discussion of papers and articles were now submitted for publication in the journal mainly as a means of recording for posterity new data or theoretical developments.

The increase in the number of staff required to deal with the growth in the publishing activities and to service the increasing membership of the two Institutes and the Institution eventually resulted in severe overcrowding of the accommodation at Grosvenor Gardens. The pressure was relieved in 1956 when the offices of the Institute of Metals were transferred to 17 Belgrave Square, but the two Institutes continued to collaborate closely and the library of both bodies remained at Grosvenor Gardens. Typical of the joint activities was the formation of a Powder Metallurgy Group in 1957 and a Heat Treatment Group in 1964.

Part of the space released by the departure of the Institute of Metals was used to re-accommodate the offices of the Institution of Metallurgists. All three bodies then collaborated in the formation and the administration of the Joint Committee for National Certificates in Metallurgy. The remaining space was rapidly filled by staff who were recruited to prepare new lines of commercial publications in an attempt to improve the financial situation. In collaboration with BISRA, the British Iron and Steel Industry Translation Service (BISITS) was started in 1957. Two years later, by arrangement with the Department of Scientific and Industrial Research, publication began of an English translation of the Russian journal Stal. Then, from 1960, the abstracts of papers in other journals and notices of new books which appeared in each issue of the journal were issued in advance of publication on index cards under the title of the Abstract and Book Title Index Card Service (ABTICS).

The membership increased only slowly during the 1950s, rising from 4909 in 1949 to 5381 in 1961, but the Institution of Metallurgists was still experiencing a robust rate of growth. Joint membership with one or both of the Institutes had been encouraged from the foundation of the Institution. This was now taken a step further in an attempt to increase the number of members. The Institution of
Metallurgists increased the annual membership fees in 1961 and each member was invited to become a member also of one of the two Institutes without payment of a further fee. The additional fee income received by the Institution was paid over to the Institutes in proportion to the number of joint members. This resulted in a period of rapid growth. The membership of the Institute rose from 7192 in 1962 to the highest total in its entire history when it reached 8625 in 1966.

For a variety of reasons, the consequences of which had not been foreseen, the Iron and Steel Institute began to withdraw from the collaborative arrangements in 1966. In that year the Institute of Metals and the Institution of Metallurgists created a Metals and Metallurgy Trust to administer the educational initiatives and most of the publishing and conference activities, but the Iron and Steel Institute chose not to participate. The offices of the Institution of Metallurgists were transferred from Grosvenor Gardens to join with the Institute of Metals in Belgrave Square and the joint membership agreement was terminated at the end of the year. The number of members of the Iron and Steel Institute immediately fell sharply. The joint membership arrangement was reintroduced in 1969, in a desperate attempt to restore the situation, but the numbers continued to decline until, by 1972, the total of 4821 members was lower than at any time since 1949. This created severe financial problems. The accounts for 1968 showed a cumulative deficit of £21,000 and the outlook was so daunting that a proposal was made at the autumn council meeting to introduce a charge of up to £20 per page for the publication of papers in the Journal of the Institute. A period of uncertainty regarding the future also arose as a result of the re-nationalisation of the industry in 1967. This was not dispelled until the BSC confirmed that it would continue to buy the services that had been provided previously for BISRA and for some of the companies that were now publicly owned.

4. CARLTON HOUSE TERRACE AND THE METALS SOCIETY

The hundredth anniversary of the founding of the Institute was celebrated with a dinner dance at the Grosvenor House Hotel and a banquet at the London Guildhall. A centenary issue of the Journal of the Institute was devoted to papers which reviewed the stages of development, the present state of the art and forecasts of future progress in each of the major fields of activity covered by the Institute. In the same year, however, a Special Committee of Finance was set up to devise a means of resolving the parlous financial state. A possible solution was proposed in 1970 when it was realised that the companies who had contributed originally to purchase the lease on the Grosvenor Gardens premises were no longer in existence, following the re-nationalisation of the industry, so there were no constraints on the use of the lease. It was decided, therefore, that an attempt should be made to transfer the offices of the Institute to the type of accommodation that was reserved for occupation by, and rented at low cost to, registered charities. Money could then be raised by the sale of the residual 43 year lease on the existing premises.
The Crown Estate Commission offered a lease of 1 Carlton House Terrace, the present home of the Institute of Materials. This property had been built in 1828–1830 and had housed several notable tenants. It was the London home of the Ambassador of the USA from 1900 to 1905. It was then occupied by the Viscount Curzon until his death in 1925. It became the premises of the Savage Club in 1936, but was severely damaged in an air raid during the 1939–1945 war. After rebuilding, the Savage Club resumed their occupancy, but the roof had not been adequately repaired. Rainwater penetrated the structure and the timberwork was soon severely affected by wet rot. Eventually, in 1963, the building was declared unsafe for occupation and the Club vacated the premises. Repairs were put in hand and, by 1970, the roof had been rebuilt but the interior was still inaccessible.

The premises were offered on an 80 year lease and without initial charge if the Institute financed the renovation of the interior at an estimated cost of £200,000. The offer was accepted. The lease of the Grosvenor Gardens house was sold for £415,000, leaving a balance after funding the renovation of the new accommodation, which produced an investment income well in excess of the annual rent of £14,500. The transfer to the new offices took place on 5 January 1972.

Meanwhile, discussions had begun in 1970 with the Institute of Metals regarding the feasibility of merging the two bodies to create a new Institute which would serve the interests of all professional people concerned with the production, fabrication and use of any or all metals. Both Institutes conceded that activities that were restricted to either ferrous or non-ferrous metals were inappropriate for the rising generation of metallurgists. Eventually a petition was submitted to Parliament to rescind the Charters of the two original bodies and clear the way to create a Metals Society. The Act was formally approved, the two Institutes merged and the long history of the Iron and Steel Institute as an independent organisation finally drew to a close on 31 December 1973. Publication of the Journal of the Iron and Steel Institute ceased from that date and the first issue of the new journal, Ironmaking and Steelmaking, was distributed in February 1974. A large increase in the membership fee in January 1972 provided an initial sound financial base for the new Institution. But the rapid increase in the rate of inflation which started shortly after the merger and continued throughout the 1970s soon caused a new outbreak of financial problems.

The total membership of the Society was showing a negligible growth rate. In marked contrast, the membership of the Institution of Metallurgists was still increasing steadily; in 1970 there were over 5500 corporate members and the total of all grades was just over 9500. The Institution of Metallurgists was granted a Royal Charter in 1975. Two years later it was admitted as a member of the Council of Engineering Institutions (replaced by the Engineering Council in 1981) and was then able to nominate members with appropriate qualifications and experience for CEng., IEng. or EngTech. registration. This inducement continued to attract new members and, despite the recession in the industry, the total was in excess of 10,000 by 1980.

The Metals Society and the Institution of Metallurgists set up a Joint Liaison
Committee in 1971 and among other issues it debated the desirability of a merger, but the Councils did not support the proposal. Co-operation was also poor. The offices of the Institution of Metallurgists were now located at Northway House in North London, which was not a convenient venue for meetings. Space was rarely made available for the Institution committees to meet at the Carlton House Terrace offices and they were held mainly at the premises of the Royal Society.

Proposals for a merger were reactivated in 1981 when a working party to consider the feasibility was set up under the chairmanship of John Hitchcock, who had played a leading role in the formation of The Metals Society. After long and detailed debate, arrangements for a merger were finally agreed in 1982. The Institution had to apply to the Privy Council to make changes to its Royal Charter, whilst Parliament was petitioned to rescind The Metals Society Act. Agreement to these changes was eventually obtained in 1984 and the Institute of Metals came into being on 1 January 1985 with a total membership of 14,000. The new body combined the professional qualifications and learned society roles in the manner that had been proposed to the Councils of the Iron and Steel Institute and the Institute of Metals in 1944.

The Institution of Metallurgists had initially admitted as members only persons with metallurgical qualifications, but the regulations had been relaxed in 1965 to admit also materials technologists and materials engineers. During the following two decades, up to the formation of the Institute of Metals, degree courses in metallurgy were gradually superseded by the more interdisciplinary materials courses. Consequently, before the formation of the new Institute had received parliamentary approval, discussions were started to further broaden the interdisciplinary base by merging with the Plastics and Rubber Institute and the Institute of Ceramics. A new working party to consider the proposal was set up in 1985 and eventually recommended to the Councils of the interested bodies that the merger should go ahead, but delays were once again experienced in achieving approval for the changes in the respective constitutions. The Institute of Materials came into existence on 1 January 1993. It can trace its origins back to that meeting in 1868 which led to the formation of the Iron and Steel Institute. The Iron and Steel Division today continues to serve the ferrous industries while the Bessemer and other medals that were originally in the provenance of the Iron and Steel Institute are still awarded annually by the Institute of Materials.

5. REFERENCES


CHAPTER 4

BISRA – The British Iron and Steel Research Association

G. D. Spenceley MBE and P. H. Scholes

1. INTRODUCTION

There has been for many years a strong tradition in Britain's steel industry for mutual assistance and co-operation in technical development. This extends back to the foundation of the Iron and Steel Institute and led to the formation in 1929 of an Industrial Research Council jointly funded by industry and government. By present-day standards, the scale of research operations was small, with the income of the Research Council initially constrained by industrial depression. These arrangements, however, did lead to valuable progress in ironmaking, steelmaking and rolling technology, and provided a deeper metallurgical understanding of steel products. They were not, however, appropriate in the post 1945 era after a war in which technological development had advanced rapidly, and there was a clear need for an iron and steel research association with its own laboratory and experimental facilities.

The research association scheme, in fact, had started in 1917 and for a time was unique to this country. In 1962, there were fifty-two research associations, which covered more than half of manufacturing industry and had a total annual income of about £7 million. The British Iron and Steel Research Association was the largest of these, with an income at that time of £1 million.

This chapter traces the background of co-operative research in the steel industry and the development of research associations, which formed an integral feature of R&D in manufacturing industry during the 1950s and 1960s. The formation and the organisational structures of BISRA are described showing how research results were promoted and applied. Some of the principal research activities are summarised to illustrate the work of the Association over a period of twenty-five years; and finally arrangements are briefly considered for the transfer of the laboratories to the British Steel Corporation, following the nationalisation of major steelmaking companies in 1967.
2. FORMATION OF BISRA

2.1 Historical Background

Co-operative research in the British steel industry dates back to the mid nineteenth century to the founding of local metallurgical and engineering societies and then, in 1869, to the formation of the Iron and Steel Institute. These organisations provided means by which people met and discussed their experiences in the manufacture and use of steel. Technical discussion helped to spread knowledge of new processes, and the speed of change and development helped to bring the industry together to consider common problems. Collaboration between companies was, however, limited by the competitive atmosphere of the times, and the industry was composed of strong-minded and individualist steelmakers.¹, ²

The initiative to set up research committees was taken by the Iron and Steel Institute during the First World War to investigate problems that were troubling the iron and steel industry as a whole. The Institute became the channel of communication between the Government's newly formed Advisory Council on Iron and Steel and the industry. However, the stimulus towards concerted action provided by the war did not long survive the ending of the war: most of the committees ceased to meet after 1921.

In 1918, the industry set up the National Federation of Iron and Steel Manufacturers (which later became the British Iron and Steel Federation, BISF) to tackle some of its major problems. It was soon realised that common commercial problems were intimately related to firm's technical concerns and that, in particular, there was urgent need for greater economy in the use of fuel. Accordingly, a technical department was set up by the Federation in 1924 to study fuel consumption and fuel economy, and the design of furnaces.³

In 1927, a renewed attempt was made by the Institute to establish collaborative work on a wide basis. A Technical Committee was set up to take responsibility for committees covering the main manufacturing processes and the work of the Committee on Metallography, which had survived the war, and its Subcommittee on Heterogeneity of Steel Ingots (formed in 1924).

The next few years saw a complete reorganisation of the central research activities of the industry. The interests of the Federation and the Institute were brought together by the formation in 1929 of the Iron and Steel Industrial Research Council. An informal division of responsibility in organising research committees was adopted. Those committees that were dealing with the processes of manufacture and the technology of production were in future organised by the Federation; and those dealing more specifically with the product and with problems of a fundamental or scientific nature were still organised by the Institute but were constituted as Joint Committees with the Federation. All committees became responsible to the Industrial Research Council. The Council was assisted by a Programme and Finance Committee, chaired by Dr W. H. Hadfield, FRS, responsible for the general direction of the various committees, and by a Scientific Advisor, Dr C. H. Desch.⁴
The principal research committees of the Industrial Research Council in the 1930s and during the Second World War are shown in Table 1. A number of other committees were also directly responsible to the Council. These included the South Wales Research Committees, the Joint Refractories Research Committee, the Industrial Furnace Research Committee and the Structure of Alloys Research Panel. Committees were also formed on Sheet Steel Development, Fire-Resisting Encasement of Structural Steelwork, Structural Steelwork Design and Sheffield Smoke Abatement.4

Of the Joint Committees, perhaps the best known is the Committee on the Heterogeneity of Steel Ingots. It was responsible for many valuable fundamental and practical studies on solidification and segregation in steel over a period of two decades. Its activities extended to the influence of ingot moulds, the physical chemistry of steelmaking, the need for accurate temperature measurement of liquid steel, the influence of gases in steel and the standardisation of methods of analysis.

The name of Dr William Hatfield, of the Brown-Firth Research Laboratories, deserves special mention in the context of the setting up of the Institute’s research committees and for his active encouragement of scientific metallurgy and the philosophy of collaborative research. Dr Hatfield chaired three of the four Joint Committees, and Mr W. J. Dawson of Hadfields Ltd chaired the Joint Steel Castings Research Committee. Dr Hatfield was supported by many distinguished colleagues, notably Dr T. Swinden of The United Steel Companies Ltd. Membership was drawn from the eminent metallurgists of the time with more than 130 organisations collaborating in the activities of committees, subcommittees and panels in 1943. The Joint Corrosion Committee was unusual in that it maintained laboratories, located in Birmingham, with a small staff under the direction of an Official Investigator, Dr J. C. Hudson.

The three principal Technical Committees reporting to the Research Council were organised directly by the Federation. The Open Hearth Committee, chaired by Mr R. P. Smith and later by Mr A. Robinson, and the Blast Furnace Committee, chaired by Mr F. Clements, were set up in 1930. The Rolling Mill Committee, chaired by Mr H. F. Wright and later by Mr H. R. Ayton, was formed two years

Table 1  Principal research committees of the Iron and Steel Industrial Research Council.
The activities of the committees reporting to the Council are detailed in a series of twenty-eight Special Reports published by the Iron and Steel Institute between 1931 and 1942, and also in the Annual Reports of the Industrial Research Council. The work of the four Joint Committees is the subject of an excellent review prepared initially by Dr Hatfield and published by the Institute. Carr and Taplin's book, *History of the British Steel Industry*, also has a useful chapter describing research activity up to 1939.

The Government's Department of Scientific and Industrial Research (DSIR) provided financial and other assistance to the Research Council. The total income was £11,000 in the first year rising to £41,000 in 1939. The general form of organisation of the Research Council was described in 1931 by an official of the DSIR in the following terms:

"... as a comprehensive co-ordination of all the research activities within the industry and of such ancillary industries as are likely to contribute to the improvement of the technical efficiency of the iron and steel industries. In addition, collaboration in research is established with steel using industries for the determination of the qualities required for particular service and the provision of suitable materials, e.g. alloy steels, heat-resisting steels and deep-stamping quality for the sections of the engineering industry concerned, e.g. aircraft, steam and electrical and automobile industries respectively. It also provides the machinery for the dissemination of the results throughout the industry, and through enlisting the services of scientific and technical personnel of the industry on the Research Committees secures the immediate application of the results obtained to industrial practice."

During the Second World War it was still found possible to continue the activities of the Research Council, particularly those dealing with fundamental studies. The Joint Committees were active throughout the period investigating problems of steel quality, corrosion, steel castings, and alloy steels. Fundamental studies on coke, blast furnace reactions, open-hearth furnaces and rolling mill practice were in progress at a number of universities and other centres. At the same time, a considerable contribution was made in connection with problems submitted by the Armed Services and other government departments. Of particular importance was the work carried out on basic refractories with a view to reducing the consumption of magnesite and increasing refractory life. Work on standardisation continued actively throughout the war, much of it directed to dealing with standardisation arising from the war effort or from the need to conserve supplies of certain iron and steel products. The Council concluded one of its reports by stating 'In many directions a stimulus has been given which will not only be of importance in the War, but will have the profoundest bearing on improving production efficiency when Peace returns.'

While not constituted as a research association in strict terms, the Research
Council did in fact come to be regarded as one, with its formal research programme covering a wide range of activities. Although it had relatively few members of staff and relied almost entirely on laboratory facilities provided by member companies, it was responsible for valuable progress in the design and operation of blast furnaces and of steel furnaces, and in metallurgical research. This progress was made through programmes of research supervised by committees with companies sharing the research work. Typically one works would undertake blast furnace trials, another would organise a series of open-hearth furnace experiments, and another would section a large ingot, possibly sending samples to be analysed in the laboratories of yet another company.⁶

2.2 Establishment in 1944 of a Research Association

After the Second World War, there was an upsurge of activity in industrial research, encouraged by the then Labour Government. It had already been decided during the war that the steel industry could no longer be satisfied with arrangements that depended so largely on the goodwill of companies in providing facilities for experimental work. The British Iron and Steel Research Association was inaugurated in June 1944 to take over and expand the work previously organised by the Iron and Steel Industrial Research Council.

A Council of representatives from the British Iron and Steel Federation, the Iron and Steel Institute, and the Government's Department of Scientific and Industrial Research (DSIR) governed BISRA. Sir Andrew McCance, FRS, was the first Chairman of Council; Mr E. Mather, Captain H. Leighton Davies, Sir Charles Sykes and Mr S. A. R. Gray succeeded him in later years. The Association's annual income was initially £70,000 from the Federation and £30,000 from the DSIR. Dr C. F. Goodeve was appointed as Director-Designate of BISRA in 1944 and laboratories were established in London and Swansea as soon as circumstances allowed, and subsequently in Sheffield and Middlesbrough. Dr Goodeve's background and naval service are described in the next section.

The setting-up of the research association was not, however, regarded by most of the larger steelmaking companies as a substitute for increasing their own research efforts. While BISRA was developing, several companies either extended their own laboratories or built entirely new facilities. Some companies preferred to carry out all their major research projects in large central laboratories serving all the operations of the company; others preferred an organisation in which research and production were more closely associated.

2.3 The Director of BISRA

Charles Goodeve was born in Manitoba, Canada in 1904. At the outbreak of war in 1939, he was Reader in Physical Chemistry at the University of London and in 1940 was elected a Fellow of the Royal Society in recognition of distinguished research studies. A Lieutenant in the Royal Naval Volunteer Reserve, he quickly became a
full-time officer with responsibilities for developing defences against the magnetic mine. This resulted in the development of the 'Double-L sweep', a device in which magnetic impulses, capable of actuating mines, were imposed upon the seabed by intermittent electrical pulses passed through floating cables. This sweep became the most important method of clearing magnetic mines from the UK's shores and harbours.7

Goodeve then turned to the problem of protecting ships directly by building up an electrical field which would neutralise the field induced by the earth's magnetism and which actuated the mines. He introduced the magnetism into the sides of a ship by raising and lowering a horizontal cable carrying a large electrical current in contact with the ship's side until the necessary magnetism was built up. The method was initially christened 'wiping', but later Goodeve invented the word 'degaussing' and the method was adopted by the Navy to cover all methods of protecting ships against magnetic mines.

Commander Goodeve was appointed Deputy Director of a new Department of Miscellaneous Weapon and Devices; the participants were known colloquially as 'the Wheezers and Dodgers'. The Department worked on a wide range of unconventional naval weapons including the 'Hedgehog', which fired a pattern of small projectiles ahead of a vessel, these being fused to explode on contact with a submarine. This proved far deadlier than the depth charge, which was dropped astern and gave the submarine too much time to take avoiding action. Following these and other outstanding successes, Dr Goodeve was awarded an OBE, and in 1942 appointed Deputy Controller, Research and Development. From then until the end of the war, the whole strategy of R&D for the Royal Navy came under his broad direction and the success of many developments owed much to his analysis of naval problems and his wise choice of priorities.

Charles Goodeve took up his position as Director of BISRA in 1945 following release from the Royal Navy. In 1946, he was knighted and awarded the United States Medal of Freedom for his contribution to Allied efforts in the war at sea. A photograph of Sir Charles is shown in Fig. 1. His wartime efforts and originality of thought, and above all his approachable attitude had a strong influence on the personnel that were recruited mainly from Universities and other centres for both fundamental and applied research activities. In 1945, more than 40 BISRA papers were published in technical journals.

2.4 Functions of a Research Association

Industry in a free country is essentially competitive, yet there are enormous advantages in having a blend of co-operation and competition, especially in research. Qualified scientific manpower is at a premium in Britain today, and is likely to remain so for a considerable time to come. It is therefore essential, as in the case of any of our scarce natural resources, that we should make the most effective use of the scientists we do have. This is one of the principal benefits of co-operative industrial research associations, by conducting research of general interest to their members, enabling individual companies to direct
their own research more effectively. In addition, because of their close relationship to their sponsoring industries, research associations reduce the possibility of duplicated research effort. The net result is a highly effective deployment of both scientific manpower and material resources.

Sir Charles Goodeve wrote these words in 1962 in an article on co-operative research in the steel industry. In this article, he questioned how the work of a research association fitted in with that carried out by the universities, by the laboratories of member firms, and by other research associations and organisations such as the National Physical Laboratory. He took the view that

... a research association such as BISRA occupies a position somewhere between that of the university and industrial laboratory. It is concerned primarily with new techniques and processes of common interest based on scientific knowledge. It prefers to support fundamental research in the universities rather than do such work in its own laboratories, unless, of course, there were special reasons to the contrary. Also it expects that firm's own laboratories will, in most cases, carry technical developments through to the production stage, carry out works' investigations, etc.
Sir Charles continued

There is no sharp distinction between the work of these three types of organisations, but the research associations do provide a necessary link between the other two. The extension of co-operative research activity in the research association does not reduce the need for research laboratories in firms' works, but indeed increases this need. These three types of organisations, the university, the research association and the works' laboratory, act more in series than in parallel.

Clearly, research of the kind conducted by research associations loses its purpose unless its results are adopted by industry. It was therefore another important function of a research association to make every effort to ensure that its industry incorporates the improvements resulting from its work as soon as possible. This need was certainly true of the steel industry where getting effective collaboration could prove to be difficult; it was here that the diplomatic skills that Sir Charles had displayed during his years in the Royal Navy were invaluable in reconciling conflicting views.

3. ORGANISATION AND ADMINISTRATION OF BISRA

3.1 Organisation

The Association's research activities covered the entire range of the steel industry's operations but perhaps with the greater emphasis on processes rather than products, the latter being mainly undertaken by the laboratories of member companies. A selection of the research activities of BISRA are described in Section 4.

There were five main research divisions, which encompassed the specific science and technology of iron and steel manufacture. The first three covered the ironmaking, steelmaking and mechanical working processes; the fourth dealt with plant engineering and energy requirements; and the fifth with more metallurgical matters. In addition to these divisions, there were three departments concerned with the basic sciences of physics, chemistry and operational research; their purpose was to study the possibilities of applying recent advances in these sciences to ironmaking and steelmaking practices. The approach of the departments was complementary to that of the divisions ensuring maximum coverage of new ideas. There was also a sixth division for steel castings research, but it was merged in January 1951 with the Research and Development Division of the British Steel Founders Association (BSFA) with the subsequent formation in 1953 of the British Steel Castings Research Association. The divisional organisation of BISRA is shown in Fig. 2. A fourth department was later formed to bring together the Association's development and information services.

BISRA also financed research contracts at Government Laboratories such as the National Physical Laboratory and at universities. In the latter case, payments took
the form either of grants to university departments or bursaries to research students. It was the policy of research associations to co-operate on investigations of common interest and arrangements existed for collaboration with fifteen other associations. Particularly noteworthy were the contributions over many years by the British Coke Research Association in work on metallurgical coke and by the British Ceramic Research Association on ironmaking and steelmaking refractories. Occasionally, the Association took part in, and contributed to the cost of, important research projects abroad such as the International Flame Research Foundation laboratories in The Netherlands and an experimental blast furnace in Belgium.

At the end of the war, the Association had practically no laboratory facilities of its own. The provision of new buildings was difficult; but a laboratory was set up for the Physics Department in a converted laundry at Battersea in London in 1946 and another for the coatings research of the Mechanical Working Division at Sketty Hall, a converted mansion at Swansea. Fundamental ironmaking research was based at Imperial College in London. Existing buildings were also acquired and adapted to provide laboratories for the rolling mill section of the Mechanical Working Division at Sheffield, for the Steelmaking Division also at Sheffield, and later for the Ironmaking Division at Normanby in Middlesbrough. The Association's Head Office was located in Old Park Lane and later in Buckingham Gate in central London. The opening ceremony in 1947 of the South Wales Laboratories at Swansea is shown in Fig. 3.
In the early years, staff were seconded to member firms and various other organisations where laboratory facilities were made available as a temporary measure. These included the Royal Naval Inspection Department in Sheffield, the National Physical Laboratory in Teddington, the Royal School of Mines in London and other research associations.

The site at Sheffield was large enough for permanent new laboratories to be built there. The first blocks were built in 1952–1953 and formally opened by HRH the Duke of Edinburgh in November 1953; they included facilities for the Metallurgy Division in addition to the Steelmaking and Mechanical Working Divisions. Later the laboratories at Battersea were extended to accommodate the Plant Engineering and Energy Division and the Operational Research and Chemistry Departments; these laboratories were further extended during the 1960s. The Sheffield Group Laboratories were also extended during this period to include a library and conference suite. Photographs from the 1950s of the Association’s three main research laboratories are reproduced as Figs. 4–6. In 1966, a new ironmaking laboratory (Fig. 7) was opened at Grangetown in Middlesbrough. The new Teesside Laboratory replaced the former North East Coast Laboratory at Normanby and the Blast-Furnace Research Laboratory at Imperial College.

One interesting feature at Sheffield was that four other specialised research bodies,
Fig. 4  The Sheffield Group Laboratories, Hoyle Street, Sheffield, showing the main laboratory block and part of the pilot plant. The main building was later extended.

Fig. 5  The London Group Laboratories, Battersea Park Road in South London. The laboratories were later extended.
Fig. 6  The South Wales Laboratories, Sketty Hall, Swansea.

Fig. 7  The Teesside Laboratories at Grangtown, Middlesbrough, showing the laboratory block and pilot plant building.
the Springs Manufacturers Research Association, the File Research Council, the Deep Forging Reasearch Association and the Cutlery and Allied Trades Research Association were closely associated with BISRA and utilised seconded staff and a part of the accommodation. These bodies subsequently moved out to premises close to the BISRA laboratories and continued to share central services.

3.2 Funding and Administration

BISRA was financed by a global contribution from the British Iron and Steel Federation and not by individual subscriptions from ordinary members. There was in addition the Government grant, which represented about 14% of total income. Other income was earned from associate member's subscriptions including members overseas, and from DSIR special assistance to industry funds, contributions from other research associations, sponsored work, and licence royalties. In 1966, there were 262 ordinary members and 139 associate members.

Table 2 shows the growth in annual income of BISRA over the two decades to 1966. The Association's accounted for only part of the industry's research efforts, in which the research laboratories of member companies played the major role. Total research expenditure in the industry in the year 1966 was about £13 million out of a turnover was £1200 million.

There were some obvious advantages from the planned geographical distribution of laboratory centres, all of which had the common purpose of promoting close co-operation between BISRA and the individual steelworks. The focal point of this co-operation, however, was the Association's committee structure. In 1966, this consisted of twenty-four technical committees whose objectives were to determine, define and assess the importance of the technical problems of the industry; and to give guidance to the research workers undertaking projects arising out of these problems. Many of the committees set up working groups for the collaborative study of problems of common interest.

The technical committees each reported to a divisional panel. The responsibilities of these panels included deciding research policy and supervision of the work. In their turn, they reported to the Council, the Association's ultimate governing body. There were also committees on finance, patents and buildings that reported

<table>
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<th>Table 2</th>
<th>Annual income and total investments (in thousands of pounds) (from the Annual Report 1967).</th>
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<tr>
<td></td>
<td>1946</td>
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<tr>
<td>Steel industry contribution through the BISF</td>
<td>130</td>
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<tr>
<td>Government grants</td>
<td>60</td>
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<tr>
<td>Other sources of income</td>
<td>11</td>
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<tr>
<td>Total annual income</td>
<td>201</td>
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<tr>
<td>Total investments in laboratory premises (at year's end)</td>
<td>3</td>
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<tr>
<td>Total investments in plant and equipment (at year's end)</td>
<td>28</td>
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to the Council. The committee structure in 1966 is shown in Table 3. The members of these bodies were recruited mainly from the steel industry, the steel-using industries, and the steel plant manufacturing industries. In many cases, other research organisations such as Government laboratories, universities, and research associations were also represented. The objective was to ensure that the research programme was in close touch with the needs of the industry and with advances in knowledge over a wide area.

The administration of research through committees has often been criticised on the grounds that it is likely to have a deadening or frustrating effect on the scientific staff. This type of committee administration, however, was considered by the Government's Iron and Steel Board, after a careful assessment made in 1963, to have been remarkably successful. The main and perhaps obvious drawback was that, with over 500 committee members, each interested in particular problems, the number of research projects was large with the result that research efforts were very dispersed.

3.3 Selection of Research Projects

At the time of the Iron and Steel Board's assessment, the Association's research programme consisted of about 200 projects. These were the projects that had survived the searching examination of the committees, panels, and Council. How were they selected? In 1962, Sir Charles described the process of selection employed by BISRA as "the marginal approach." The six steps in this approach are listed below.

1. A regular study is made of the needs, opportunities, and future investment plans of the industry.
2. Members of staff, with their knowledge of science and technology, are brought into contact with these needs and, consequently, from time to time, have ideas as to how a particular need could be met.
3. The idea is developed in discussion until it can be classified as a potential project.

4. Both existing and potential research projects are repeatedly assessed in priority in terms of the related need of the industry and the promise of the idea being successful in meeting the need. Only those projects having a high need and good promise qualify for inclusion in the research programme, and those with a very high need or a very good promise are given priority.

5. The existing research resources are deployed over the qualifying projects.

6. The marginal projects, i.e. those that just fail to get in to the programme, and those that just get in, are then re-examined in the light of a possible change up or down of the existing research and development resources. The judgement to increase, or reduce, the resources is made as objective as possible, by means of wide consultation, for example, at committee meetings.

Having completed this procedure, comparisons were made with other industries bearing in mind that those close to an industry do not always fully appreciate its problems and opportunities.

3.4 Application of Research Results

For maximum acceptance of research results, it is essential for the research organisation to maintain a continuous outward flow of information. The principal method of communicating information arising from its work was the research report. These were first submitted to the appropriate research committee, being classified at this stage as 'confidential' to that committee. If the committee then considered that the report should be made available to all the members of the Association it was reclassified as 'restricted' and listed together with a short abstract in a Report List. This two-monthly publication was circulated to all member companies with copies of reports then available on request.

The Report List was usually accompanied by three or four project summaries. These were condensed accounts of work to which the Association wished to draw particular attention as being close to the application stage. They were designed to give the reader a rapid understanding of the project concerned and thus enable a decision on whether more detailed information would be of value. All reports, summaries and publications issued by BISRA, with the exception of the 'confidential' reports, are listed in the Annual Reports of Council published during the period 1945 to 1969.9 More than 250 reports were being written by BISRA staff each year during the 1960s.

Another of the methods for promoting research results was the organisation of BISRA conferences. Largely restricted to members to permit unfettered discussion, most of these conferences were annual events. Besides affording a further opportunity for the Association to report its work, they also served a broader purpose in providing an occasion at which steel managers presented papers and exchanged information and experiences in both formal and informal discussions. The
Ironmaking, Steelmaking, Mechanical Working and Chemists Conferences issued proceedings, some with a verbatim record of discussions, which were subsequently published. There were in addition the conferences of The Iron and Steel Institute where BISRA staff played a prominent part in presenting accounts of research often in conjunction with staff from member firms.

Having ensured that the interests of members had been fully served, information about research activities was then distributed as widely as possible. Many of the previously ‘restricted’ research reports were reclassified as ‘open’ reports, some were published in the technical literature; and news releases and summaries were issued to the press. Press demonstrations, exhibitions, laboratory visits for specialist groups and regular laboratory open days were organised, all designed to give the information the widest possible distribution and thus secure the maximum application of the Association’s research in industry. (Figs. 8 and 9).

The Patents Committee kept the commercial future of a project under constant review. In 1966 for example, the number of licence agreements issued for the manufacture and sale of plant and instruments, which had arisen from BISRA work, amounted to more than eighty. Notable among these were systems for automatic gauge control in rolling and automatic power input control (for electric furnaces); and the processes of compact annealing, Elphal and Plasteel coating, electroslag refining and continuous casting. In some cases, a separate exploitation company was formed, for example, the Electroslag Refining Technology Unit and Spray Steelmaking Ltd.

Fig. 8 Open Day at the South Wales Laboratories.
Fig. 9 Demonstration of continuous casting at the Sheffield Group Laboratories.

The Development and Information Services (DIS) assisted in the exploitation of research results. This department was formed in 1959 to bring together staff involved in the application of letters patent, public relations, information and libraries, materials and standards, and the provision of technical assistance and liaison services to members and others. The work of the technical service units is illustrated in Section 4.24. DIS Liaison officers paid regular visits to member firms to discuss current research, and in particular to aid in the effort to obtain application of results. These visits were valuable for examining problems of mutual interest and general matters, which might not have been previously considered.

3.5 Staff

During the early years, there was heavy reliance on extra-mural Research Officers from universities, research associations and Government laboratories, who were engaged wholly or partly in work in conjunction with BISRA. Some of these transferred to the Association as Sir Charles gathered a nucleus of staff. The number of scientific, laboratory and administrative staff employed by BISRA increased from 100 in 1946 to more than 700 in 1966; about 30% of staff were graduates. Many graduates and post-graduate employees spent only a few years in the laboratories before moving back to academic life or taking up appointments in manufacturing industry in Britain or abroad; several became leading executives in major steel
companies. Others spent many years in BISRA becoming industry experts in their specialist fields. The Association was in fact a technological training ground with many foreign graduates gaining a first experience of the steel industry and its problems, and then returning to their own countries to take up management posts.

The Heads of Divisions and Departments during the life of BISRA were as follows:

- Ironmaking Division: Dr H. L. Saunders, Mr E. W. Voice,
- Steelmaking Division: Mr R. H. Myers, Dr A. H. Leckie, Dr J. Pearson,
- Mechanical Working Division: Dr H. Ford, Mr W. C. F. Hessenberg, Dr J. G. Wistreich, Mr W. N. Jenkins,
- Plant Engineering and Energy Division: Mr H. H. Mardon, Dr H. R. Mills, Dr J. G. Wistreich,
- Metallurgy Division: Dr M. L. Becker, Professor G. Wesley Austin, Dr W. E. Duckworth, Dr R. L. Craik,
- Steel Castings Division (merged with the BSFA in 1951): Dr W. C. Newell,
- Physics Department: Mr (later Professor) M. W. Thring, Mr J. Savage, Mr W. C. F. Hessenberg, Mr S. S. Carlisle, Dr R. V. Williams,
- Chemistry Department, Dr (later Professor) F. D. Richardson, Dr J. Pearson, Dr S. Klemantaski,
- Operational Research Department: Mr R. H. Colcutt, Mr D. H. Kelley,
- Development and Information Services Department: Mr L. W. Stevens-Wilson, Mr B. A. Jessop.

Mr W. C. F. Hessenberg was appointed Deputy Director in 1950 and in later years Dr J. Pearson, Mr E. W. Voice, Mr S. S. Carlisle, Dr J. G. Wistreich and Dr W. E. Duckworth were appointed Assistant Directors. Mr T. Dennison was Honorary Consultant.

4. SELECTION OF WORK UNDERTAKEN

In this Section, a range of activities have been chosen to illustrate research and development during the period 1944 to 1969. This period includes two of the transition years when BISRA was designated as The Inter-Group Laboratories of the British Steel Corporation. The aim of this chapter is to provide some appreciation of the extent, depth and creativity of the contribution made by describing projects that were commercially successful and those that were not. There is often much to be learned from the latter, where the research work receives less publicity and may eventually be forgotten. The work summarised here has been selected from many hundreds of project activities with time scales varying from a few months to several years. In no sense is this intended as a comprehensive account of the research undertaken. Major projects associated with outdated processes have been omitted, or mentioned only briefly, for example, exploitation of low-grade indigenous iron
ores, advancement of open-hearth steelmaking, Bessemer converter steelmaking, and improvement of ingot casting technology and structural studies of ingots. Work on steel castings, steelmaking and improvement is not covered. Relevant technical reports and published papers are listed in the BISRA Annual Reports 1945–1969.

4.1 Blast Furnace Raw Materials

In the blast furnace process, consistency of chemical and physical properties of the burden has long been recognised as a vital factor. This was reflected in the technical work undertaken covering iron ores, coal and coke, pelletising and sintering.

4.1.1 Iron Ores

Early work in the late 1940s and 1950s included a number of studies on the concentration of British ores including Oxfordshire ironstone and marginal Northamptonshire ironstone. Recommendations were also made for the handling of imported iron ores ranging from ship design, unloading and movement of ore in the works. In 1960 a survey of stocking and blending facilities concluded, we might now think humorously: 'It is clear, however, that while home-ore users can blend effectively, many foreign-ore users would need extravagant installations to accommodate the irregular deliveries of certain ores'.

Breakdown of lump ironstone, whether undesired during transit to the blast furnace or by design for subsequent agglomeration, was an important area for study. BISRA co-operated closely with the work of the International Standards Organisation (ISO) Committee on Physical Testing of Iron-bearing Materials leading to a draft specification for an international tumbler test for pellets, iron ores and sinter. Test procedures were also established for measuring the physical stability of ores, pellets and sinter during heating and reduction.

4.1.2 Coal and Coke

In 1947, a Coke Research Joint Committee was formed with the British Coke Research Association (BCRA). This Committee provided a forum for inter-plant comparisons of coke size, degradation and quality. The Royal College of Science and Technology, Glasgow, which had access to an experimental coke-burning rig and industrial furnaces at the Clyde Iron Works of Colvilles Ltd, undertook supporting research. Studies included investigations on the 'raceway' effect with the raceway length being related to the velocity of the air blast, tuyere diameter and coke size. Rates of reaction between coke and iron bearing slag were also investigated.

The BCRA opened a new Coke Research Centre at Chesterfield in 1959 and this became the centre for research. The equipment included a full-scale test oven for carrying out work on a scale directly comparable with industrial practice. The major objective of the sponsored research programme was the improvement in the quality and yield of metallurgical coke. Physical properties of coke considered to be
important were the need for a narrow size-range, high impact strength and high abrasion resistance.

An experimental rig (Fig. 10) for studying coke combustion was built in the late 1960s at the Teesside Laboratories to establish the reasons for variable breakdown of coke, in production blast furnaces, not explicable by measured physical properties. The plant was designed to allow a detailed study of the mechanism of combustion in the raceway for various cokes. Gas compositions measured at and above the tuyere showed minimal sensitivity to cokes with different reactivity test coefficients. A variant of the coke combustion rig at the Teesside Technology Centre continues to be a valuable research tool for studies on coke quality and solid and gaseous fuel injection.

4.1.3 Pelletisation of Iron Ore
In 1950, the British Iron and Steel Federation was concerned about the nation’s sintering capacity and commissioned studies on the development of the technique for pelletisation of Sierra Leone concentrate with attention to the influence of grain size, water content, and organic and inorganic additions. A pilot-scale pelletiser rated at 500 kg h\(^{-1}\) was built in an experimental building at the Redcar Works of Dorman Long (Steel) Ltd. for these evaluations. Initially, grinding of the ore was found to be necessary with firing at 1300°C following balling in an inclined drum using an inorganic binder. Subsequently it was demonstrated that wet milling was better than dry grinding and that a mix of wet powder with Sierra Leone fines fired with 3% coke incorporated gave satisfactory pellet properties. Blending of Sierra Leone fines with Swedish and other ores was also shown to be feasible without using sodium carbonate solution as a binder.

Over the next decade, pellets were shown to be an excellent feedstock for the
blast furnace helping to increase productivity and reduce coke rate. All pellets produced commercially were made from finely ground concentrates and there was renewed emphasis on minimising grinding costs by the pelletising of coarser material. It was shown that commercial grade pellets could be produced from relatively coarse ore mixes but the pelletisation and firing processes were more critical. Studies were undertaken on the use of an annular kiln for pellet firing and the ability to produce pellets from sinter mixes. Research was also extended to study the production of fluxed pre-reduced pellets by mixing anthracite and slaked lime with fine ore. A 20% fuel addition was found to be necessary to give about 80% reduction.

In addition to the work on pelletising using inclined discs and drums, other methods of agglomeration of iron ore fines were investigated. In 1952, ore concentrates were fed onto an oscillating corrugated surface, which caused the material to form pea-size pellets that were subsequently sintered. Briquettes of mixtures of iron ore, lime and silica sand were also made but were of inadequate strength after firing.

4.1.4 Sintering of Iron Ores
Sintering research throughout the 1950s and 1960s was aimed largely at ensuring that new and existing plants in the UK were used at maximum efficiency to deal with the iron ores that were available at the time particularly concentrates and super-fine materials. In the early 1950s, permeability was known to be a controlling factor in sinter plant output with the quantity of air needing to be kept constant for a particular sinter mix. The addition of burnt lime to mixtures of foreign ores showed that air requirements could be reduced and sintering times shortened. Research revealed some of the causes of variation in the quality of sinter in British plants and enabled better control to be achieved. It demonstrated how varying the permeability of the sinter bed could regulate output. It also highlighted the need for effective cooling of the hot sinter and this prompted comparative studies of the efficiencies of cooling systems.

Work continued in the mid 1950s to explain the factors controlling the sintering process. Certain aspects of the process were shown to be common to all materials, including chemically inert materials of widely different water contents, and also carbonates and iron ores. When the bulk density of the bed is low, the flame front travels through the bed at a faster rate and the temperature at any point of the bed rises and falls faster when the density is high. Hence, the quantity of air needed to sinter a given mass of material is always of the same order. In addition, the quantity of heat needed to produce a given temperature distribution throughout the bed is very similar.

The effects of changing the nature of the fuel and the amount of oxygen in the sintering atmosphere were also studied. In a sinter bed, the hot zone caused by transfer of heat from the upper layers and the zone of burning fuel start together and then travel through the bed at the same rate; this accounts for the high temperatures reached. With a highly reactive fuel and extra oxygen, the fuel burns
faster, the flame front travels ahead, and the two zones no longer coincide. This creates a broader, combined hot zone at a lower temperature. Relationships were also established between airflow and suction at various depths in the sinter beds for various fuel contents.

In the late 1950s, there was a worldwide trend in the operation of blast furnaces with high proportions of self-fluxing sinter. The Association demonstrated that the strength of fluxed sinters was influenced by the temperature of sintering, specifically the peak temperature and time at high temperature. Provided that the gangue content of the sinter bed did not exceed about 30%, strong super-fluxed sinter could be made which did not disintegrate on standing.

In work aimed at controlling sintering conditions to give the desired structure, studies of fluxed sinters revealed that a strong reducible sinter had a uniformly disseminated, interconnected pore structure with little glazing on the pore surfaces. The iron was present mainly as secondary hematite; no olivines were present, and a glass containing very little iron was the main bond.

With the increase of evidence that sinter charged to the furnace should be free from fines, emphasis was placed on the problem of separating fines from sinter. The fundamentals of screening were determined. In initial work, high efficiency could only be obtained with screens vibrating at low amplitude and frequencies, and a low feed rate, but for high capacity, a more vigorous vibration was necessary. Linear motion was superior to circular motion; this yielded high efficiencies during vigorous vibration, which inhibited screen blockage and afforded higher throughputs at smaller deck inclinations. This work concluded in 1967 with the way open for operators and designers to take advantage of the significant and quantitative effects of the many variables identified in the research.

Work in the mid 1960s was strongly focused on sinter testing using a sinter box test rig at the Teesside Laboratories (Fig. 11). The requirement was for quantitative data to examine the adverse effect of certain fines and concentrates, which included the cheapest sources of iron units. Earlier work had exposed the need for a generally accepted test method for sinter strength with no prospects at the time of international agreement. Following extensive plant trials, the ASTM method was accepted as the standard test to determine strength indices as the basis for future work. It was evident that reduction of ultra-fines content must be related to the price of the ores and concentrates, and to the level of productivity required. Two techniques were available for overcoming the adverse effects of the high ultra-fines content: the use of additives such as burnt lime and improvement of sinter feed preparation in which the -12 mm fraction was taken out, balled and remixed with the other constituents. As part of this study, tests were made to establish the effect of the chemical composition of sinter mixes on the mineralogical phases present in the sinter and on its properties.

4.2 Ironmaking Processes

Fundamental and applied research on ironmaking processes was a major feature of
the research programme each year from 1945 to 1969. The following paragraphs illustrate a small part of this work.

4.2.1 Blast Furnace Exploration

The main theme of research in the early 1950s was to find ways of exploring the blast furnace and studying the contour of the stockline and rate of descent of the burden. Among the techniques employed was the use of radioactive tracers both in the burden and in the refractory lining. This provided residence time data for lumps in the inactive zone, beyond the combustion annulus. Tracers were used to compare transit times of furnace gases at different points on the stockline when the furnace was operated with different proportions of sinter.

A mechanical exploration device, known as the ‘fishing line’, was used to relate changes at the stockline to charging cycles, blowing practices and so on. Field trials indicated considerable differences in the conditions of the stocklines between furnaces with marked change in the depth of the V shaped contour with increasing blowing rate. The rate of descent, as shown by stockline observation, could not always be taken as a reliable indication of gas flow in the upper stack.

Calculation of heat flow through carbon hearths emphasised the high tempera-
tures involved with possible danger to the furnace, both in and below the hearth.
Although water-cooling had been used elsewhere, it was suggested that adequate
thermal control could be secured by air-cooling. Heat flows were established and
design recommendations made for the foundations of a new furnace. At the central
axis, the whole layer of carbon in the hearth is above the freezing temperature of
the iron. In addition, the increase in thermal conductivity of the carbon by graphi-
tisation and iron impregnation depresses the freezing contour by about 0.75 m,
thus endangering the concrete foundations.

Little was known in the 1950s about the actual distribution of metal and oxide
phases within the reduced zone of the furnace and how this might vary with dif-
ferent ores. Reduction proceeded from the surface of a lump of ore in a stepwise
fashion; zones of free iron, wustite and magnetite being separated by narrow tran-
sition zones. The nature of the ore, the gas composition and reduction temperature
were factors all shown to affect the relative thickness of the iron and oxide zones.

A study of the tuyere zone of the furnace established the ‘raceway effect’ and the
behaviour of the raceway under certain combustion conditions. Increasing the
blowing rate increases the penetration rather than the width or height of the race-
way. An increase in coke size has the opposite effect: penetration is reduced and the
width and depth of the raceway increased. Changes in blast temperature had less
effect on combustion than might have been expected at the time.

4.2.2 Blast Furnace Performance
There were no reliable methods in the early 1950s for the assessment of furnace per-
formance. Statistical analysis of operating practices was limited by the lack of com-
puting power. Nevertheless, attempts were made to forecast furnace behaviour
with sufficient precision for assessment of the effects of raw materials. In 1953 the
Ferranti computer at Manchester University became available for more exacting
analyses of variance. Later, more detailed studies were made of weekly furnace
records of British furnaces using the Pegasus computer installed at the
Association’s Head Office. The data was analysed by statistical methods derived
from formulae proposed by workers in Europe and the United States. Statistical
treatment of data was subsequently refined over a period of several years in co-
operation with workers abroad.

4.2.3 Fundamental Studies
With the co-operation of Shelton Iron, Steel & Coal Co. Ltd., a small-scale blast fur-
nace with a hearth diameter of 53 cm was constructed and operated in 1944 for a
period 13 weeks. The studies on the pilot blast furnace were aimed at achieving a
better understanding of the chemical reactions and burden behaviour in the blast
furnace process. Between 1948 and 1951 the Shelton plant was also used in support
of studies on the injection of solids and gases through blast furnace tuyeres. It was
shown that substantial amounts of limestone could be introduced through the tuy-
eres without causing any noticeable chilling of the hearth. In 1949 proposed exten-
sions of this work included the injection of various fuels including pulverised coal,
fine ores and oxygen. Work in this field proceeded only at a low level over the following ten years.

In the mid 1950s, a method was conceived for simulating conditions in the stack of a furnace under controlled conditions. This was the static charge in a controlled environment (SCICE) project designed for studying the chemistry and kinetics of blast furnace reactions. The equipment consisted of a container for charging with burden materials with the facility for circulation of gas of controlled composition in the closed system. A unit was constructed and installed at the laboratories at Battersea in 1959 with the intention that it would form the centrepiece of future research into blast furnace reactions.

4.2.4 Fuel Injection
BISRA activities in the field of tuyere injection were resurrected in 1961 with computer programs being developed to predict material and thermal balance when injecting solid, liquid or gaseous materials. By 1962, eleven member firms had conducted full-scale trials with tuyere injection of fuel oil with four companies using the technique on a routine production basis. During that year, BISRA was also associated with trials in conjunction with Stanton and Staveley Ltd and the National Coal Board on the pneumatic injection of crushed coal. There was also an interest in the injection of oil/coal slurries and oxygen enrichment of the blast. In the latter case, by 1964/1965 oxygen enrichment of the blast up to 26 per cent by volume had been achieved with heavy fuel-oil injection at rates of up to 76 kg t⁻¹ of hot metal.

4.2.5 Alternative Ironmaking
In the mid 1950s, there was considerable interest developing on new ironmaking methods and BISRA was requested to undertake theoretical and experimental work. The aim was to produce iron from fine ores and coal, thus making ironmaking independent of coking coals. A 'Cyclosteel' process (subsequently renamed Flame Smelting) was conceived in which an initial preheating and pre-reduction stage was to be followed by a final reduction and liquid metal slag separation stage. A reactor pilot plant was constructed for the second phase in which finely divided coal was gasified with oxygen to provide a suitable atmosphere and temperature for reduction of iron ore fines leading to the production of hot metal (Fig. 12). By 1959, the production of liquid metal and slag was demonstrated although some technical problems remained not least in the proposed fluidised bed pre-reduction stage. The project was terminated in 1963 following an economic study, which concluded that for UK conditions the cost difference benefit compared with the blast furnace would not be sufficiently great.

Arguably, the most ingenious alternative ironmaking process was embarked upon by BISRA in the late 1960s. This was the Continuous Ironmaking Process (CIP). The basic concept was to reduce iron ore concentrates by fine coal in a vessel reactor operated at high rotational speeds so as to centrifuge the constituents of the furnace and spread them in a uniform film around the inner surface. Under the
action of the centrifugal field the various liquid and solid constituents segregated into separate layers; the heaviest constituent, iron, was maintained as the outer layer against the refractory surface, thus protecting the refractory from attack by liquid iron oxide. Heat generation and transfer in the core of the reactor were to be achieved by the introduction of oxygen to combine with carbon monoxide generated from the smelting reaction. A Clf pilot plant, designed for a throughput of one ton per hour of iron, was constructed and operated at the Teesside Laboratories (Fig. 13). The basic principles of the process were demonstrated with molten iron being produced. However, the engineering and operational complexity of the process precluded its adoption as a viable alternative production method for making liquid iron.

4.3 Oxygen Steelmaking

An important function of BISRA was its role in bringing together experts from
throughout the British steel industry to discuss and develop process operations. This was particularly exemplified by the activities and collaborative studies of three working groups that were set up by the BISRA Steelmaking Committee in the 1960s to study oxygen converters.

4.3.1 Collaborative Studies

The Oxygen Converter Working Group comprised plant managers from companies operating LD, Kaldo, Rotor and VLN steelmaking processes. In addition to being a forum for exchange of information and experience, topics investigated by group members included oxygen-lance practice, scrap consumption and its enhancement by preheating and the addition of silicon carbide, the quality of lime, and the preheating of hot metal. The Group also provided a focus for meetings with the Oxygen Converter Committee of the Association Technique de la Sidérurgie Française (ATS).

The Oxygen Converter Engineers Group was responsible for the study of engineering problems associated with factors such as vessel design, vessel distortion, tilt drives, trunnion assemblies, and bearings and bearing housings. Two other important fields of study were the overlay welding repair of oxygen-lance copper nozzles and automated methods for the rapid exchange of an unserviceable oxygen lance by a second lance mounted in a standby position connected to services.

The Converter Instrumentation Group was concerned with the measurement and control of steelmaking processes. This was an area of major challenge with much work in the 1950s and 1960s by BISRA and its member companies aimed at developing effective methods of controlling the process. The membership of the Group was drawn from plants operating a wide variety of converter processes, that is, acid and basic Bessemer, VLN, LD, LD-AC and Kaldo steelmaking plants. The essential problem of all these processes was the inability to measure in situ the bath carbon content and temperature during the course of blowing. This made the converter batch processes inherently difficult to control with reliance having to be placed on predictive calculations and indirect measurements.

Some very novel methods of measurement were tried particularly on Bessemer
plants in the late 1950s with turn-down carbon content being indicated by measurement of the flame radiation at the mouth of the vessel using an infrared analyser. This reflected the decrease in the evolution of carbon monoxide towards the end of refining. Attempts were also made to measure bath temperature using radiation pyrometers sited through a hole in the converter shell and lining, and through a basal tuyere. Thermocouples with ceramic sheaths were also inserted through the wall of a Bessemer vessel at Workington.

Later developments included the use of audiometers to measure sound emission from the converter to indicate the level of slag foaming in the vessel, and also off-gas analysis, which was a major step forward in understanding and measuring the amount and rate of decarburisation. The proceedings of the 70th BISRA Steelmaking Conference in 1968 give an excellent account of the status of developments at that time.\(^{10}\)

Work on converter control continued during the transfer period of BISRA to the British Steel Corporation with particular emphasis on the development of process models in association with spot temperature and composition measurements and indirect measurements. These studies further highlighted the difficulties of controlling a batch process where the slag and metal were not in chemical equilibrium during the refining process. This led to the novel proposal by BISRA to make the process more amenable to control by stirring the bath during refining, thus ensuring that the slag and metal were closer to chemical equilibrium. A converter pilot plant built at the Sheffield Group Laboratories demonstrated the principle giving savings in yield and alloys. Variants of the process are now in routine production use throughout the world.

4.4 Electric Arc Steelmaking

The commissioning in 1952 of an experimental 500 kg arc furnace (later enlarged to 1250 kg) at the Sheffield Group Laboratories enabled fundamental studies on electrical and operational aspects of arc furnaces to improve operating efficiency (see Fig. 14).

4.4.1 Power Input Control

Roof temperature measurement by thermocouples revealed a close relation between roof wear and maximum temperature reached. This suggested that continuous roof temperature measurement would be a useful basis for control of the power input. Inadequate thermocouple sheath materials led to the alternative use of a total radiation pyrometer sighted on the inside surface of the roof, through a hole in the sidewall of the furnace. When the rate of roof temperature rise indicated that power was being dissipated wastefully, a signal to the power input control system activated a reduction in power input by shortening of the arcs. For application on production arc furnaces, variants of Automatic Power Input Control (APIC) were developed including the use of a signal from a power integrator to terminate the high voltage period. In the early 1960s, considerable benefits resulted from the application of APIC to production furnaces of up to 80 tons in size.
Reductions of up to 10% in specific power consumption were achieved together with up to 17% reduction in electrode consumption. APIC was licensed to a number of manufacturers in the UK, Japan, France and Germany.

The availability of the experimental arc furnace also provided the opportunity to study other electrical aspects of furnace operation including those listed below.

- Cine photography of the arc paths (in 1957) showed that, in general, the arcs kept to the outer edges of the electrodes but during refining moved towards the centre of the bath under short arc conditions.
- A voltage disturbance analyser was designed to study permissible levels of voltage fluctuation (flicker) produced in the mains supplies.
- A six-electrode arc furnace was proposed to give better arcing, faster melting and less voltage disturbance.
- Silicon carbide coating of graphite electrodes offered the promise of reducing graphite loss.

4.4.2 Steelmaking Developments

Metallurgical studies on the distribution of sulphur between slag and metal indicated that the slags were capable of removing more sulphur from the melt during double slag reducing periods. The furnace was also used to demonstrate successful melting of pre-reduced iron ore pellets from Stelco-Lurgi and from processed iron sands supplied by New Zealand Steel.
4.5 Oxy-Fuel Steelmaking

In 1961, trials commenced at Sheffield to establish the possible use of oxygen-oil burners for the melting of cold charges. These took place in the converted 500 kg capacity arc furnace using a burner of toroidal design developed by Shell International Petroleum Co. Ltd. Charges consisting of scrap and cold pig iron were melted in about 30/40 minutes with no significant emission of iron oxide fume. This early work was to develop in three ways: for assisting melting in electric arc furnaces; for decarburising liquid melts without associated fume formation; and as the basis of a complete steelmaking process from cold iron units, as an alternative to electric arc steelmaking. This latter development became known as the Fuel Oxygen Scrap (FOS) process.

4.5.1 Assisted Melting

By firing through the door of an arc furnace, a Shell toroidal burner was used to accelerate the melting of stainless scrap at Spartan Steel and Alloys Ltd. resulting in a productivity increase of 25%. Oxy-fuel assisted steelmaking became routine practice during the 1960s and it is now used throughout the industry. Initially oil was used as the fuel but subsequently gas and most recently fine coal have been employed.

4.5.2 Fumeless Refining

During the early development of the FOS process, it was observed that melt decarburisation took place without the heavy fume emission associated with the use of oxygen alone. Trials in association with a number of steelmaking and foundry companies were undertaken to determine whether the method was viable on production plants.

The trials took place initially on a 2.5 ton scale at the Rutland Foundry of Samuel Osborne & Co. Ltd. These were followed by 30 ton trials at the River Don Works of English Steel Forge and Engineering Corporation Ltd and then by 2.5 ton trials to refine stainless grades at the Low Moor Alloy Steelworks of Osborne Steels Ltd. It was demonstrated that decarburisation could be achieved by directing the combustion products from oxy-fuel burners at the surface of the melt using oxygen input rates in excess of the stoichiometric oxy-fuel ratio. Despite this success, environmental pressures at the time were demanding the installation of fume cleaning equipment for all stages of melting and refining. Another factor was that control of decarburisation was not easy because of the intermediate role of the oxidation state of slag in the refining process.

4.5.3 The FOS Process

Following the success of the initial small-scale melting trials, further extended trials took place at Dowlais Foundry and Engineering Co. Ltd. (2 ton scale) and on a pre-refining vessel of 30/40 ton capacity at Brymbo Steelworks. These studies provided the basis for an economic evaluation of the process after which the Federation's
Technical Efficiency Committee recommended central financial support for a large-scale trial under production conditions using a vessel specifically designed for FOS operation. Dorman Long (Steel) Ltd, in consultation with BISRA, designed and constructed an 80 ton vessel at their Cleveland North Works. Supporting studies during this period included model work on furnace design and burner location (Fig. 15), pilot-scale melting and refining trials at the Sheffield Group Laboratories, oxy-fuel burner 'boring-down rate' trials using a full-scale ladle assembly and evaluations of various burner designs.

Commissioning work on the 80 ton FOS vessel started towards the end of 1967 (Fig. 16). Sixty-four heats were produced before the trials were discontinued because of excessive refractory wear associated with high refractory temperatures during refining. The refining period was a crucial stage of the process because of the need to have sufficient carbon in the melt at meltdown with subsequent decarburisation providing the superheat for casting. At this stage of the process, there was no independent method available for controlling the carbon content of the melt, carbon being supplied via the pig iron in the charge. Insufficient carbon at
melt out led to excessive iron oxidation under flat bath conditions with poor heat transfer from the oxy-fuel flame.

More recent converter developments of bath agitation in association with coal additions could provide the key to carbon control and thus process viability should the FOS process be revisited in the future.

4.6 Continuous Steelmaking

Oxygen converter steelmaking, being a batch process, is inherently difficult to control because of the absence of steady state conditions. This contrasts with many industries, for example, the chemical industry, where continuous processing is
practised. Thus, continuous steelmaking became the Holy Grail for steelmaking scientists in the late 1950s and early 1960's.

In the 1960 Annual Report the concept was disclosed that if a stream of molten blast furnace metal is atomised by a suitable arrangement of oxygen jets, there is rapid oxidation and refining of the metal. It was considered that such spray refining should be a simple and inexpensive method for pretreating iron to make it suitable for finishing to steel in any type of furnace or converter at rates matching the requirements of the finishing process.

4.6.1 Spray Steelmaking

An experimental unit was constructed at the laboratories in Sheffield with oxygen supplied from a ring manifold atomising a molten iron stream and with collection of the refined droplets in a transfer ladle. Following promising results, a pilot plant was designed for pretreatment of hot metal by spray refining at the Redbourn Division of Richard Thomas and Baldwins Ltd. Trials on this plant demonstrated effective desiliconisation of liquid iron. An economic assessment however indicated that the costs would be of the same order as for ladle desiliconisation. This conclusion led to a redirection of the work to removal of carbon by spray refining as a step toward continuous steelmaking. The principles of spray steelmaking are illustrated in Fig. 17.

![Fig. 17 Principles of spray steelmaking process.](image-url)
A new experimental plant was built to investigate more fully the conditions for injection of oxygen and lime powder for removal of silicon, phosphorus and carbon. Extensive trials demonstrated adequate removal of silicon and phosphorus from hot metal containing up to 0.6% phosphorus. Carbon contents of less than 0.05% were also achieved in a single pass through the spray plant. Pilot plant work was supported by single-droplet studies using a high-frequency induction unit and graphite susceptor designed to allow a single drop to fall through an oxygen atmosphere into a quenching fluid.

In 1965, an experimental production-scale plant was constructed at Millom Haematite Ore and Iron Co. (Fig. 18). Hot metal from the blast furnace runner was gravity fed to the top of the spray unit with the major objective being the production of refined and special irons for use in the foundry at Millom. A steelmaking rate of 36 t h\(^{-1}\) was achieved with the production of refined steels with carbon contents in the range 0.02–1.2%.

The Millom trials were followed by the construction of a full-scale production
prototype unit at Lancashire Steel Manufacturing Co. Ltd., Irlam. Operations commenced in February 1967 with iron throughput rates of up to 50 t h\(^{-1}\). Shelton Iron and Steel Ltd. were also assisted in the design, construction and operation of another spray steelmaking reactor that was mounted above a Kaldo vessel, with the vessel used as a receiver. The aim of both these units was to obtain comprehensive data for the economic assessment of the spray steelmaking process.

In July 1967, responsibility for spray steelmaking was passed to Spray Steelmaking Ltd, a wholly-owned subsidiary company of BISRA. Further extensive trials took place both on the production scale and at the Sheffield Group Laboratories. Several associated developments were demonstrated including continuous metal elevation using an electromagnetic conveyor and also continuous alloying and deoxidation, showing the technical viability of this radically different process route to steel based on the exploitation of continuous operations. Development of the spray steelmaking process continued into the 1970s but, unfortunately, it was not possible to demonstrate commercial viability in economic terms.

At the time of the spray steelmaking development, several of the larger foreign companies were also working on some form of continuous steelmaking. Almost all were basing process development on blast furnace iron as the feedstock with scrap as the coolant. On reflection, the radical change to continuous operation was aimed at a relatively small step in the processing route to steel (i.e. hot metal refining) with the need still to batch liquid steel prior to and after the continuous refining step. Greater cost saving potential exists if one can exploit continuity going from iron ore to steel. Recent developments in alternative ironmaking processes have been directed at this objective.

4.7 Electroslag Refining

Electroslag refining (ESR) is a process in which a consumable electrode feedstock is remelted and refined via and through an electrically heated synthetic slag, the refined product being solidified in a water-cooled mould. The method was designed to reduce the phosphorus, sulphur and inclusion contents of steel and improve mechanical properties.

4.7.1 Process Development

The Association began trials in 1961 with slags containing 70% CaF\(_2\), 20% Al\(_2\)O\(_3\), and 10% CaO. It was shown possible to remove about 70% of the sulphur and 60% of silicon in steels with some slight loss of manganese, phosphorus and nitrogen. A large proportion of the inclusions present in the steel feedstock was successfully removed, those inclusions remaining in the solidified refined steel being much smaller and more evenly spaced than in the original material. The slag composition had to be tailored to the types of inclusion: a slag containing Al\(_2\)O\(_3\) removed a large number of silicates present but resulted in a pickup of alumina particles, while
slags containing CaO were efficient sulphide removers. The first laboratory pilot plant produced 150 mm long ingots in square and round sections, up to 100 mm in size, in water-cooled copper moulds. Alloys could be introduced during the remelting process by additions to the slag.

In 1964, a large-scale ESR plant was built in co-operation with a member company for ingots of up to 150 mm diameter × 400 mm long. Some eighty ingots were made in a wide variety of qualities including stainless, maraging and die steels, but with the major industrial interest at the time being in the production of high-speed steels. Carbide segregation was reduced and soundness and cleanness were improved. The plant was controlled by a system devised by The United Steel Companies' Swinden Laboratories in which the actual melting current was compared with the desired current. The error signal acted to displace the electrode, thus producing a change in circuit impedance through the slag pool and causing a change in melting current.

The effect of melting current on the ingot surface was more marked in the lower current ranges with the best surface produced using slags containing titania. Lower melting currents gave flatter solidification fronts and generally sounder ingots with better removal of large inclusions. Pickup of aluminium and oxygen from the slag was less marked than with higher currents. The effect of increasing current and increasing electrode diameter was to increase melting rate but specific power consumption was unaffected.

The greater power available with the larger plant enabled departure from the conventional calcium fluoride type slag and the development of others containing, for example, 50% CaO with the balance either TiO₂ or Al₂O₃. Although highly efficient as sulphur removers, these two slags tended to increase the aluminium and titanium contents of the steel. One problem encountered was porosity at the bottom end of the ingot, often taking the form of elongated blowholes characteristic of hydrogen evolution. This led to an examination of the role of moisture when using lime-bearing slags. Improvements were achieved by the use of a very high starting current to ensure the formation of the molten pool and the evolution of any moisture present.

ESR compared favourably with consumable vacuum arc refining, particularly at low levels of plant utilisation. The essential advantages were less electrode preparation before refining, improved ingot yields, better surface finish after refining and greater flexibility of ingot shape, and importantly the capital cost of plant was reduced.

By 1966, the research had identified the importance of operating conditions. Operational parameters determined the soundness of the ingot, whereas slag characteristics determined the degree of refinement. Exceptions to this general rule were molten pool depth, which influenced refining capacity, and slag viscosity, which could influence ingot quality. The high ingot yields of the process along with improvements in product quality were confirmed in many evaluation trials. It was observed that ingot yield could be enhanced by means of a molten slag starting procedure.
4.7.2 Commercial Exploitation
Co-operative work ended in June 1966 with the formation of a self-financed unit, Electroslag Refining Technology (ESRT), to exploit and develop the process independent of the Association’s research programme. This was the first example of the successful application of research results by means of a special development and promotion unit formed within BISRA. Five plant manufacturers were associated with the unit. Figure 19 shows the growth in the number of plants installed (outside of the USSR) during the period 1964–1968, and the number of these plants that were associated with ESRT.

In 1968, ESRT commissioned a 375 kVA plant to produce ingots, 380 mm diameter x 3 m long, in most types of alloys. The facilities provided allowed the successive tandem feeding of short electrode feedstock to produce these long ingots.

Electroslag refining is now a well-established route for the manufacture of high integrity products, for example, for the aerospace market.

4.8 Continuous Casting
After seven years of theoretical and experimental work by the Association at the laboratories in Battersea, a satisfactory method of continuous casting was brought to the stage of commercial application in 1954. Development work was transferred to Sheffield with commercial exploitation pursued in parallel with continuing research studies. There were other important developments in the UK at this time, notably the innovative research of a team of The United Steel Companies, under the
leadership of Mr. I. Halliday. In the early 1950s, this team realised the high-speed continuous casting of billets on a pilot plant at Barrow Steel Works.

4.8.1 Machine Development and Industrial Application

In November 1950, a series of Open Days was held to demonstrate the work of the Physics Department at the London Group Laboratories in Battersea. Continuously cast ingots were on view with surface qualities as good as commercial ingots. With the introduction of spring mounting for the copper mould, the repeated casting of 75 mm diameter bars at speeds of 0.6 m min⁻¹ was feasible. One important aspect of laboratory work was the need to understand the process of heat transfer and friction during freezing to establish methods of increasing the casting speed. There was particular emphasis at the time on the casting of alloy steels and experiments with high-speed steels showed that the friction between steel and mould was much greater than for carbon steels and the average rate of heat transfer from steel to mould was higher.

A development group of twelve companies financed the construction in 1953 of a two-strand pilot plant of BISRA design at William Jessop & Sons Ltd in Sheffield. The plant was designed for the experimental production of 100 mm square billets of alloy steels, primarily high-speed steel, from a furnace charge of 1.5 tons. The accuracy of mould alignment was one factor shown to be of particular importance during the testing of this plant. The new process was independent of any foreign patents and the high yield, of 90%, of continuous casting was seen at the time to be a particularly attractive feature.

Research progressed with the construction of a pilot plant incorporating a spring-mounted mould and able to cast 100 mm square sections about 6 m in length. A wide variety of steels of qualities ranging up to 18/8 stainless grades were cast to provide test material for examination and fabrication by member companies. Withdrawal rates were the main focus of the initial work with rates of up to 1.8 m min⁻¹ achieved. Broadly, the experimental casts compared well in quality to rolled and forged products from ingots of similar specifications. The central porosity of billets was welded up by a relatively small reduction in area, but quite large reductions were required to produce material of satisfactory mechanical properties.

A second pilot plant came into operation in 1957 with the facility of casting lengths of up to 6.7 m, with the later addition of secondary cooling enabling casting at speeds of up to 3.7 m min⁻¹. Design studies of the spring-mounting assembly of the mould led to the introduction of a reciprocating mould with a compression-release principle.

Towards the end of the 1950s, it became increasingly evident that continuous casting was more suitable for bulk steel manufacture and research was focused increasingly on the casting of slabs. One problem was the bulging of the wide face under ferrostatic pressure. If the slab bulged with an appreciable force, the friction between strand and mounted rollers could prevent product withdrawal. For this reason the rollers down one side of the machine were individually mounted on
spring-loaded bearings. The modified BISRA experimental plant was erected at the Abbey Works of Steel Company of Wales and used successfully to cast slabs 700 mm wide \times 125 \text{ mm} thick fed from a 50 ton capacity ladle. Over the next two years, this machine was used for investigating the influence on blowhole formation of the state of oxidation of low carbon steel and on the improvement of surface quality, shape and mould vibration.

In 1960, The Steel Company of Wales ordered a twin-strand plant for the casting of 1220 \times 200 \text{ mm} slab sections based on the system developed by BISRA and the Continuous Casting Co. Ltd. This was the first installation of its type in Europe designed for the casting of rimming steels and the first in the world to operate with converter steel. Unfortunately, the casting of rimming steel compositions proved not to be viable because of the lack of control of gas evolution in the mould. After termination of this work, research effort was redirected to the casting of special sections as described in the following paragraphs.

4.8.2 Weybridge Multi-Mould Casting
In 1961, the Continuous Casting Co. Ltd of Weybridge and BISRA jointly commenced development work on the casting of interconnected triple mould sections (Fig. 20). Liquid steel was poured from a single tundish nozzle into the central mould section from which it flowed through the channels into the outer moulds.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig20.png}
\caption{Triple-mould cast sections.}
\end{figure}
Prior to or during subsequent rolling the individual sections were separated by oxy-acetylene cutting or by shearing. The purpose of the development was to substantially increase throughput rate for the casting of small sections. Initially the individual sections were 75 mm square with 125 mm section sizes being produced later.

The first commercial plant to use the Weybridge process was Western Canada Steel Co. in Vancouver where 30 ton heats were cast into triple 138 mm square sections. Supporting studies by BISRA included mould design and product bending. It was also demonstrated that five inter-connected billets could be produced from a single, centre-section liquid feed.

4.8.3 'Dog-bone' Casting
The success of interconnected mould casting opened up the possibility of casting other section shapes and in 1964, BISRA in collaboration with Algoma Steel Corporation Ltd of Ontario, Canada, demonstrated the feasibility of casting of 'dog-bone' shaped sections as a feedstock for beam rolling (Fig. 21). Short lengths of continuously cast blanks were produced using the Sheffield pilot plant and welded to conventionally produced blanks prior to processing the full length to the desired beam section on the Algoma wide flange mill. The quality of the surface and the internal structure of the processed 'dog-bone' was similar to that of standard

Fig. 21 'Dog-bone' mould blank.
material. Rolling trials on beam blanks also took place at Lanarkshire Steel Co. Ltd and Appleby-Frodingham Steel Co. with beams of high quality being produced. Based on the above studies and with continuing BISRA work on mould design and metallurgical properties, Algoma Steel Corporation ordered the first production continuous casting plant for the casting of 'dog-bone' sections. The twin-strand plant was commissioned in March 1968 and in July 4000 tons of beam blanks were produced. The larger blanks were rolled to $610 \times 305$ mm and $610 \times 229$ mm beams while the smaller blanks were processed to $356 \times 171$ mm, $305 \times 254$ mm and $305 \times 165$ mm (Fig. 22). It was anticipated that four mould sizes would accommodate the full range of eleven beam sizes produced by Algoma. Beam blank casting was licensed to Concast AG and applied at plants throughout the world.

4.8.4 Thin Slab Casting

In 1967, studies commenced on the production of a thin slab direct from a continuous casting plant with in-line deformation by rolling of a cast oval section. An experimental pilot plant was constructed to investigate the feasibility of the concept and, in the initial trials, plain carbon steel was cast into an elliptical section mould of dimensions $381 \times 63.5$ mm. A squeeze cast reduction of up to 40% was applied. Metallurgical examination of the as-cast structures revealed internal cracks and segregate formation at the solidification front. Hot rolling was shown to heal the internal cracks with adequate strip properties being obtained. The BISRA concept was also investigated for the casting of stainless steels but internal cracking and segregation still represented a difficult problem.

The developments of in-line strip production in the 1980s and 1990s have taken the concept of thin slab casting to commercial realisation on mini-mills using varia-

Fig. 22 Continuously cast beams at the Algoma Steel Corporation.
ious combinations of shaped moulds and progressive in-line reduction of the cast section with a liquid core. It could be argued that the BISRA development was abandoned too soon. What was regarded at the time as an inherent and insurmountable problem was subsequently alleviated by later technological developments.

4.9 Reheating Furnaces

It was estimated in 1965 that improvements in the control and design of slab reheating furnaces could cut the industry's fuel bill by about £1 million/year. This provided the impetus to a major investigation into furnace chamber design and the temperature history of slabs passing through the furnace. The data obtained enabled the development of mathematical models of the heating process and the dynamic behaviour of the furnace and its influence on control and design. The most important findings were as follows:

- The soaking zone served only to reduce the severity of skid marks and did so at the cost of some loss of overall slab temperature.
- The skid marks absorbed 15–25% of the heat produced.
- The recuperative system absorbed barely 35% of the heat content of the waste gases.

Subsequent investigations covered furnace design and skid systems, burner design and instrumentation, slab temperature measurement, waste heat recovery and furnace chamber shape.

Computer calculations of the temperature distribution in slabs pushed over water-cooled skids led to a new design of skid. A wearer bar of high-temperature resistant alloy was affixed to a refractory insulated, water-cooled skid of triangular cross section (Fig. 23). Prototype test work in a production furnace showed no signs of wear and slab temperature gradients (or skid marks) at discharge averaged 10°C instead of the previous 30°C (Fig. 24). It was also shown that it would be possible to reduce the surface area of the water-cooled pipes by 30% thus saving on costs.

Ceramic recuperators were redesigned to achieve greater efficiency of waste heat recovery. The silicon carbide tubes were glazed and, in this way, air leakage was reduced from 10 to 1% based on trials with a twenty-five tube experimental recuperator for over a year. Full-size recuperators were life tested in the reheating furnaces of BSC's Ravenscraig and Scunthorpe Works in 1969.

Research on furnace chamber design produced better computational techniques for working out chamber geometry and burner flame shape to achieve the desired zone temperature profile for slab reheating purposes. Aerodynamic model studies ensured that pressure distribution specified in the chamber was acceptable. In 1969, a three-burner experimental furnace was built with variable geometry so that a wide range of furnaces and flame shapes and slab temperatures could be simulated.
In parallel with work on furnace efficiency, a computer control system was developed to integrate furnace control into the type of overall mill control that was being introduced in the mid 1960s. The aim was consistency of slab temperature to within ±10°C and minimum fuel consumption, when the slab-pushing rate was varied to suit the pacing of the strip mill. The first complete digital control system was brought into use in 1969 at the hot strip mill of BSC's Spencer Works. As a result, the temperature variation of slabs entering the mill was halved.

Fig. 23  BISRA-designed skid for reheating furnaces.

Fig. 24  Comparison of slab temperature profiles of BISRA-designed and conventional skids.
4.10 Rolling

In 1945, research groups based at Cambridge and Sheffield Universities formed the nucleus of co-ordinated research activities guided by the BISRA Rolling Committee. The fundamental work at the Cambridge Cavendish Laboratory by Dr Orowan and his colleagues was aimed at the plastic deformation of metals during rolling while practical studies on an experimental cold rolling mill at the Sheffield Group Laboratories, under Dr H. Ford, dealt with measurements of roll force, power consumption, effect of rolling reduction and speed. These early studies were to provide the basic information for major contributions by BISRA on the mechanics of rolling and automatic gauge control.

4.10.1 Mechanics of Rolling

The main theme of the Association's rolling mill research during the first few years was the evolution of improved theories of rolling as a preliminary to the development of more accurate methods of calculating the loads, power consumption and other important variables in the process. The origin of this work was a paper published by Dr Orowan entitled 'The Calculation of Roll Pressure in Hot and Cold Flat Rolling'. There followed a number of publications by Ford, Ellis, Bland, Sims, Cook, McCrum and other BISRA research workers on methods and data for the calculation of load and torque in cold and hot rolling mills. Some of these are still in use today.

4.10.2 Automatic Gauge Control

The improved understanding of the mechanics of rolling led in 1950 to proposals for improving the control of gauge thickness in rolling processes. Two methods based on the use of a roll force meter were devised. The first proposal used the principle that roll force is directly proportional to the thickness of the outgoing strip for a given screw-down setting and that roll force could be modulated by applying tension to the strip. In this method, the tension control gear was electrically connected to the roll force meter so that tension was automatically adjusted to keep the roll force constant. The second proposal was based on the principle that if a change in roll force was accompanied by a proportional change in the screw down setting and while the proportional factor remains equal to the elastic coefficient of the mill, the strip remains constant in thickness.

The tension method for automatic gauge control (AGC) was successfully demonstrated in the laboratory on a two-high, 250 x 250 mm experimental mill followed by trials on a four-stand cold reduction mill at John Summers & Sons Ltd. In the latter case, the gauge speed effect encountered during starting and stopping was eliminated. In the meanwhile, the Association's 150 x 125 mm mill was converted to hydraulic roll loading for trials of the screw-down control concept (known as the 'setting' method). The trials were successful in demonstrating the principle of gauge control with the screw-down mechanism being deployed when the strip thickness departed from that desired by more than a preset amount. In
1953, laboratory studies on automatic gauge control were transferred to a newly installed, four-high mill at the Sheffield Group Laboratories, shown in Fig. 25. BISRA took out a number of patents covering the control methods and for a new type of gauge meter. Exploitation was in collaboration with Davy and United Engineering Co. Ltd with the first industrial installation being on a reversing cold reduction mill at the Lancashire and Corby Steel Manufacturing Company. By 1956, several installations were being built for the UK and elsewhere in Europe, and in North America. In 1957, the control concepts of screw-down and tension control were applied with conspicuous success on a four-stand, cold strip mill in Canada.

Following the agreement in 1952 between BISRA and Davy and United Engineering Co. Ltd, a joint research and development team was set up on automatic gauge control. Shortly afterwards virtually all members of the BISRA team joined the staff of this company, which no doubt contributed strongly to the successful exploitation of AGC.

4.10.3 Lubrication and Wear
The availability of the well-instrumented, experimental four-high mill in the laboratories at Sheffield provided the opportunity for study of the lubrication process in cold rolling. New rolling oils from a member company were compared with conventional soluble oils with substantial reduction in rolling-loads being obtained.
However, none of the experimental oils proved better than palm oil. Fundamental studies demonstrated the importance of lubricant viscosity and the effects of wear debris in the rolling process, which could also be correlated with simple strip compression tests. The hydrodynamic component of lubrication was predominantly a result of bulk entrapment of lubricant and not to micro-entrapment in surface irregularities. The amount of bulk entrapment varied with rolling speed and lubricant viscosity, and appreciably influenced the surface finish of the strip. The presence of wear debris on the rolls was beneficial with the retention of wear debris on the roll surface being influenced by the surface texture of the roll, e.g. the direction of surface grinding marks. Lubrication in hot rolling was studied in the post-BISRA period with beneficial effects particularly in the production of special sections.

The change in roll profiles that was caused by wear during the hot and cold rolling of strip, and the hot rolling of rod and sections, proved to be difficult problems in the BISRA period. Frequent roll changes were necessary during cold rolling, while in hot rod rolling pass changes were required with associated re-setting of the mill and entry guides.

In the early 1960s, it was established that a thin layer of hard electroplated chromium (less than 0.025 mm) applied to the surface of the rolls of a cold rolling mill resulted in a substantially lower rate of roll wear (by a factor of 3); this also gave a more consistent surface finish to the strip. The method was adopted for routine production use at the works of a member company. It was also demonstrated that a thin layer of chrome on a textured roll surface would allow the texture to be retained for a longer period.

The electroplating of rolls with chromium was not suitable for hot rolling because of thermal crazing. In a different approach, a surface coating containing tungsten carbide was tested on a rod mill finishing train with the trials demonstrating the potential for achieving a three to five fold increase in roll life. Unfortunately, the technology for applying carbide coatings, for example, by welding, was not realised at the time of this work and it was not possible to make sintered tungsten carbide rolls of the size required. This latter type of roll can now be made satisfactorily and their use is now a standard feature in rod rolling plants.

Effective roll cooling in the hot rolling of flats and sections is a crucial factor in minimising wear and ensuring retention of the correct roll and product profiles. Heat transfer studies in the 1960s at the Battersea Laboratories and at the works of member companies provided the basic understanding and designs for cooling which are still of value today.

4.11 Forging and Extrusion

In the late 1940s, a Solid Mechanics Section was formed to provide a theoretical background to the problems of producing wrought metals and in particular to extend the plastic field theory of plasticity to anisotropic materials. The theoretical work was closely linked with tests on plasticine models that were shown to behave like a metal when deformed. The stress–strain curve of plasticine when under com-
pression was measured and various forms of forging and extrusion gave strain distributions very similar to those calculated from theory and shown by metals. Plasticine has greater sensitivity to rate of strain than for most metals, but was considered to be quite suitable for model experiments in metal plasticity.

Some of the early studies on forging used plasticine to investigate the variation of mechanical properties with forging strain, the strain being inferred from plasticine models (Fig. 26). The aim was to determine the forging strain to give optimum mechanical properties. In a continuation of this work in 1957, plasticine studies demonstrated that the number of strokes and passes needed to produce a desired change in the size of stock differed considerably according to the forging schedule used. This led to an investigation using plasticine and steel to determine the relationships between spread and elongation on shape, width and penetration of the forging tools and on the dimensions of the forging.

An urgent need for improved mechanisation of the forging process was identi-
ified in 1956 to minimise manpower requirements and this became a major research area for the forging team at Sheffield over the next eight years. One of the first steps was to install an experimental forging stock manipulator on the 200 ton press. The rail-bound manipulator interlocked with the press to provide a fast working, high precision plant. The experimental forging plant enabled the development and demonstration in 1964 of the completely automatic operation of optimum forging schedules determined from the plasticine/steel model studies (Fig. 27). Many of the features demonstrated at that time were taken up by the industry including such companies as Park Forge Ltd, Henry Wiggin and Co. Ltd, and Jessop-Saville Ltd. Other techniques investigated in forging included the use of heat reflectors and high heat flux, infrared heaters with the aim of reducing or eliminating reheating during the forging process. These trials also demonstrated better temperature control and yield in the forging of alloy and heat-resistant steels.

Apart from the earlier plasticity studies on extrusion using plasticine, BISRA research on extrusion of hot steel did not commence until the mid 1950s. By using an extrusion press at the University of Birmingham and with supporting plasticine model studies, a method was demonstrated for eliminating the discard of material that traditionally contributed toward significant yield loss in the process. The potential of hot extrusion for consolidation of feedstock central porosity and for the dispersal of segregates and carbide networks was demonstrated for tool and alloy steels. Extrusion ratios of up to 60:1 were achieved with good surface quality. Lubrication and die design were shown to be critical factors. The concept of direct hot linkage of casting and extrusion was proposed and trial production processing of high-speed steel semis by extrusion of hot-stripped ingots was successfully

Fig. 27 Demonstration of automation in forging using an experimental manipulator and hydraulic press with interlocked controls.
achieved. Unfortunately, the scale of operation and plant required was not viable for the many small producers that were a feature at that time of the tool steels industry; thus the hot extrusion of steel remained a process with unfulfilled potential.

In the mid 1960s methods were explored to produce shaped forgings, such as rolls, blanks, gears, shafts and rings, by combining forging and extrusion techniques using closed lubricated dies in a forging press. Pilot production trials with a range of alloy steels confirmed that sound products of good dimensional accuracy with minimum yield loss could be produced. The viability of this near-net shape, one-shot forge/extrude process depended greatly on tooling costs and batch requirements at that time. The field of closed die forging has developed considerably since this work with multistage processing and precision forging.

4.12 Wire Drawing

The initial programme of research in wire drawing was overseen by the BISRA Drawing Committee which was formed in 1945 with the remit: 'To compile and evaluate existing information together with various investigations to determine the forces that are called into play in the manufacture of wire and the effects of varying conditions on the properties of drawn wire'. Initial studies were concerned with the mechanics of wire drawing with information being obtained on wire drawing variables, such as drawing load, die pressure and type of deformation. A split die technique was used for much of this work.

An early novel subject was the concept of die-less drawing by hot stretching. The process involved the stretching of wire while it was being rapidly heated, followed by water quenching. Experiments showed that bright drawn mild-steel wire could be reduced by as much as 50 to 60% at temperatures of between 800 and 1000°C. The method of heating itself was important in minimising wire breakage with induction heating being superior to flame or electrical resistance methods. It was concluded that the margin between steady running and fracture was less than wire drawing through dies and therefore of only limited commercial interest. Over subsequent years, the major topics of BISRA research in wire drawing were lubrication and wire cooling.

4.12.1 Lubrication During Wire Drawing

In the early 1950s, methods of minimising friction during drawing were unsatisfactory with die wear often being excessive. The role of wire coating and that of lubrication was not understood and it was this that became the objective of the initial research work. The electrical resistance between the wire and die was shown to be a good indicator of the thickness of the lubricant film during the drawing process. This method was used on production machines to evaluate wire coating and lubricant practice. Studies undertaken on improving lubrication can be illustrated by the investigations below.
• The application of an electro-deposited soap film on the wire at die entry.
• The vibration of the soap powder lubricant in the entry soapbox to improve wire pickup during drawing.
• The use of a hydrodynamic forced-feed system for the lubricant, patented by Professor Christopherson of the University of Leeds. This involved the movement of the inlet wire through an oil-filled tube sealed into the bell of the die. Viscous shear forces created by the wire movement could generate sufficient pressure during drawing to separate the wire from the die by a film of oil. Extensive research work by BISRA demonstrated the feasibility of the principle using solid lubricants; and in 1956 a ‘Soap Nozzle’ was designed and tested for use on production wire drawing machines.

Some ten years later, interest in forced lubrication in wire drawing was resurrected with work commencing on wet lubrication by mineral oils externally pressurised at $345 \text{ MN m}^{-2}$ in a suitably constructed die unit with an inlet seal at one end and the reduction die at the other. The method was proven by tests on the pilot plant and demonstrated on a production machine. Industrial trials of high-pressure lubrication are illustrated in Fig. 28.

4.12.2 Cooling During Wire Drawing
Heat is generated in the wire drawing process and on multi-hole machines, if the wire is not cooled between passes, then the mechanical properties of the wire will deteriorate. Heat transfer studies in the mid 1950s identified the contribution to heat removal by heat transfer to the capstan and by convection to the atmosphere.

Fig. 28 Industrial trial of a high-pressure lubrication system for wire drawing.
The most effective solution to the problem, direct water cooling of the wire between drawing passes, was not considered viable at the time because of potential drawing lubrication problems. Less dramatic, but still worthwhile, improvements in heat removal were indicated by forced convection and changes to the design of the wire drawing capstan. Effort on the latter was selected for detailed engineering studies particularly relating to heat transfer from coolant water at the internal capstan wall.

A new design of wire drawing capstan was proposed with enhanced heat transfer created by an annular gap promoting turbulence in the internal cooling water. Tested in the pilot plant and on production machines, this narrow gap capstan design was adopted by machine manufacturers allowing a 25% increase in throughput compared with conventional machines.

In 1969, the potential for direct water-cooling of wire during wire drawing was reassessed. A system incorporating water sprays and an air wipe was used at the exit of the die before the capstan. Laboratory tests were successful at drawing speeds of up to 300 m min\(^{-1}\) and were followed by demonstration on a production pant. The method was adopted for routine use.

4.13 Strip from Powder

In 1962, an important strategic object of the Mechanical Working Division based at Sheffield and Swansea was the direct production of thin strip. The process first studied involved the continuous reduction of thin layers of iron ore but the reaction rates meant that this could not be achieved with a pilot plant of realistic length. A second method involved the deposition of iron powder by electrophoresis with simultaneous electrodeposition, but the ratio of electrophoretic to electrolytic deposition was not sufficiently high. A third method involved the deposition of iron powder onto a substrate prior to rolling and heat treatment. Finally, there was the technique of direct powder rolling in which the powder was fed into the nip of a rolling mill to produce a continuous compact for subsequent processing. A major effort was deployed by BISRA on the latter two concepts and this is described in the following paragraphs.

4.13.1 Low-Carbon Strip Production

The method developed at the South Wales Laboratories in Swansea was to mix iron powders and a binder to form slurry, and then coating a temporary substrate to the desired width and thickness and drying to form a non-adherent self-supporting film. The film was removed continuously from the substrate and roll-compact to form a green strip. A flash heat treatment removed the binder and partially sintered the strip, which was then subject to further rolling and in-line heat treatment. An experimental plant was built to demonstrate the concept (Fig. 29) and material up to 250 mm wide and 0.25 mm thick successfully produced in the laboratory. Metallography revealed a structure and properties comparable with that of conventional tinplate material.
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Fig. 29 Experimental plant for manufacturing low-carbon steel strip from powder.

The viability of this process was strongly influenced by the cost of the iron powder with water-atomised mild steel offering the best possibility. Powder produced from water atomised, 3 ton induction melts at BSC's River Don Works provided the mild steel feedstock for technical and economic evaluations. The process was further developed at the Shotwick Laboratory in the post-BISRA period with the production of coils for commercial evaluation. Although technically very promising, the process was not adopted on a production scale since this would have necessitated replacement of existing strip mill capacity for tinplate production, which also included the economics of scale of operation. Further studies continued on the production of special alloy strip that is now exploited outside British Steel plc.

4.13.2 Direct Rolling of Stainless Steel Strip from Powder

The initial attempts at producing 'green' strip from powder involved the use of impellers to direct the feedstock into the roll nip of a conventional vertically-oriented rolling mill. Green compacted strip of uneven density was obtained associated with the pulsed feeding method used. For the throughput rates required for stainless strip, it was shown that this problem could be overcome by gravity feed of the powder into a horizontally oriented mill. Laboratory trials at Sheffield demonstrated the feasibility of the process including the sintering and further compaction required of the 90/95% density green strip.

An experimental continuous line was built in the laboratory to process 100 mm wide coils of sintered green strip for subsequent cold rolling and annealing.
Mechanical properties of powder rolled material were almost identical to those of conventionally produced material and with comparable drawing properties. In 1969, coils of up to 100 m in length were produced for extensive customer evaluation including tests for corrosion resistance. The processing of strip from a powder feedstock is illustrated in Fig. 30.

The British Steel Corporation later installed a 15 ton capacity stainless-powder production facility at the Stocksbridge Works to provide the feedstock for a prototype 1.5 m wide powder rolling plant with associated sintering facilities installed at the Shepcote Lane Works in Sheffield. Successful commissioning of this plant was achieved in 1977/1978 with the production of strip up to 1 m wide. Product benefits were demonstrated but the development was not considered commercially viable at that time.

Fig. 30 Processing stainless steel strip produced by powder rolling.
4.14 Rapid Annealing of Strip

Laboratory work in the 1950s on the continuous annealing of blackplate indicated that it would be possible to shorten the annealing cycle from about 3 min to less than 10 s by using liquid metal as the heat transfer media. This was clearly of great significance in reducing the pass length of the annealing line and thereby the capital and running costs. Initially it seemed necessary for the shortened cycle to be followed by an overaging treatment at 300°C after coiling, and for this treatment a protective atmosphere would be needed during and after coiling. However, further work showed that a protective atmosphere was probably not necessary since, for a range of steel compositions, hardness values comparable with those achieved in commercial practice were obtained with overaging below the minimum oxidising temperature of the mild steel strip.

Can-making trials with 125 mm wide strip confirmed that the 'temper universal' properties for tinplate could be achieved with a processing time of less than 10 s. This was followed by the construction of a pilot line with liquid metal and direct resistance heating to achieve this rapid annealing cycle. The plant was used initially at speeds up to 45 m min⁻¹ to determine best operating conditions and to produce material for user assessment. Investigation of the hydrodynamic aspects of strip entering a liquid at high speed showed that submerged rolls rotating in the opposite direction to strip motion, or jets of water directed along each side of the strip, also in the opposite direction, removed troublesome boundary layers and reduced frictional drag. A new compact annealing furnace for 125 mm wide strip was commissioned in 1963 incorporating contra-rotating rolls and which was suitable for process evaluations at speeds up to 150 m min⁻¹, the minimum required for tinplate applications.

For the production by critical annealing of can-end stock of consistent properties from material with different carbon contents, automatic control based on continuous hardness monitoring was required. An in-line magnetic hardness monitor was designed and built for this purpose and installed after the furnace section. Resulting information allowed the design of a production prototype for installation on a full-width continuous annealing plant.

The trend in the tinplate industry in the mid 1960s was towards the production of lighter, stronger tinplate. With the BISRA rapid annealing process, new hard grades of tinplate could be produced without recourse to double reduction, an operation known to limit ductility and accentuate directionality. The 125 mm strip compact plant using liquid metal for heat transfer successfully demonstrated the possibility of rapid annealing for future development. A new range of products was envisaged, using normal grades of steel, by varying the cycle of annealing.

By the second half of 1964, the experimental plant was being used for the supply of trial material for appraisal by potential users of the process, which had been licensed to seven British and three foreign manufacturers. Further developments in the process would have necessitated the construction and operation of a full-scale production prototype furnace and such expansion did not take place.
4.15 Strip Coating Processes

Fundamental studies in the late 1950s resulted in the development of a series of innovative processes for the coating of steel strip and sheet with organic materials and metal powders. This can be exemplified by brief descriptions of the Plasteel, Pacplate, Videlac and Elphal developments.

4.15.1 Plastics Coatings

The Plasteel coating process was developed for the continuous bonding of PVC on to steel strip and sheet. A pilot plant was built to operate this process on continuous strip, of widths up to 150 mm, with the use of various types of PVC films ranging in thickness from 0.035 to 0.30 mm with plain, embossed and printed finishes. It proved unnecessary to phosphate the steel surface as in other laminating processes. The laminate could be readily pressed, formed, deep-drawn and punched without damage. The decorative and protective properties of the coating were suitable for new applications, such as wall panelling, TV cabinets, and switchboard panels. Other coating developments were aimed at bonding films to steel of tinplate gauge for the manufacture of cans. Work on the Plasteel process was completed in 1958 with four British companies engaged in building production plants.

There was further work on the manufacture of plastics-coated steel by using a liquid plastisol, composed of PVC polymer, plasticiser and stabiliser, instead of a calendered film. Attention then turned to the use of a PVC powder, since this was the cheapest form of PVC at the time and had the additional advantage of allowing curing of the adhesive and gelling of the plastic in one operation. Thin pore-free coatings were successfully produced on blackplate by rolling a dry, blended powder on to hot, adhesive coated strip. The objective of this process, known as Pacplate, was to produce an inexpensive coating that would have a wide field of use, including the replacement of glass containers. In 1961, a licence was granted to a French company to manufacture plant for the Plasteel process with other licences granted to member companies for the production of laminates.

4.15.2 Strip Lacquering

The possibility of using plate with tin on one side and lacquer on the other side together with the development in the mid 1950s of lacquered blackplate in the USA suggested research into strip lacquering. An experimental machine was built to study the behaviour of roller-coating systems and curing cycles with various lacquers, particularly those based on epoxy resins. Coatings of 0.00025 mm of phenolic-modified epoxy resin, cured at about 300°C, were obtained which had negligible porosity and remained free from cracking at an elongation of up to 30%. The main problem in providing a high-speed process was the long curing time of the lacquers then available and electrophoretic deposition of a partially cured lacquer offered an alternative to avoid this drawback. While high rates of deposition would be possible with epoxy-polyamide resin emulsions, the use of the more common epoxy-phenolic type was held up for the lack of a sufficiently fine resin. Curtain coating
techniques would allow operations at line speeds in excess of 150–180 m min\(^{-1}\) for a coating of 0.00025 mm thick. This phase of the work ended in 1959.

Studies of glow discharge polymerisation led to the later development of the Videlac process for the ultra high-speed deposition of lacquers using electron-beam radiation and vacuum techniques, without the use of a solvent. An experimental plant was constructed in 1967 for the simulated processing of 2 m lengths of 0.5 m wide strips for product evaluation, particularly for shelf life trials. Valuable assistance was received concerning the irradiation of lacquer coatings from the Atomic Energy Establishment at Harwell.

The target for this development was continuous coil lacquering at speeds of 180–300 m min\(^{-1}\) to operate in-line with existing electrolytic tinning and tin-free lines. It was shown that a wide range of materials could be cured by electron bombardment in a vacuum. Widespread interest in the research work at the Swansea Laboratories led in 1969 to a design for a high-speed production facility using standard vacuum equipment, which offered substantial savings in comparison with conventional lacquering.

4.15.3 Aluminium Coatings

The use of an electrophoresis process for deposition of ground resins from a suspension led to the development of a method for applying finely-powdered aluminium to sheet and strip. Following initial trials with small samples, an experimental 125 mm wide process line was constructed at the South Wales Laboratories in 1961 (Fig. 31). When produced under optimum conditions, the properties of the aluminium-coated steel, known as Elphal, were most attractive, particularly in withstanding corrosion and high temperatures. The coating was shown to be uniform and thickness could be controlled to fine limits. Very little alloy layer was present and porosity was so low that the surface could be anodised; and the steel could be deformed without deterioration of the coating. Material costs were 50% higher than when using ingot aluminium for hot dipping, but this was offset by the fact that so little alloy was present and that the coating proved to be much more uniform in the powder-based product.

The first commercial plant began production in 1963. With growing interest in Elphal, extensive studies were made of the three-stage process (deposition, compaction and heat treatment) and the bonding mechanism. A fund of empirical knowledge was acquired and this was applied to the application of other metal powders including nickel, stainless steel and other alloys. It became apparent that the three-stage process of powder deposition had wider implications within the concept of a versatile coating line able to produce coatings of different compositions. In the later stages of the work, a dry powder coating was developed as an alternative to electrophoresis to make the process capable of rapid change of product and to facilitate high-speed deposition.

The Elphal process was subject to intense interest and by 1964 plant manufacturing and user licences had been granted to twelve companies. By 1966 commercialisation of the process had passed to industrial companies, but competition from improved hot-dipping processes was to prove decisive.
4.16 Plant Engineering

Plant engineering research was centred on the London Group Laboratories at Battersea covering the design, maintenance and control of iron and steelworks plant, equipment and services; the handling and transport of materials and products; and the use of energy in all its forms. The nature of this remit meant that there was involvement with numerous projects and a strong interface with the operations of member companies. This work is exemplified in the following paragraphs.

4.16.1 Automation

The progressive application of automation was a significant aspect of technical progress in the industry, and the development of automation systems formed a key component of new process technology. Typical development work in the BISRA laboratories included:
• the development of a hydro-mechanical method for measuring and controlling
gauge in rolling processes using a capsule inserted between the chocks and mill
screws,
• enhancement of metallic yield by optimising teeming weights in ingot casting
and in the cutting of billets to length,
• control system development based on dynamic modelling of the blast furnace,
• dimensional control of billet, bar and rod mill rolling, including bar gauge meas-
urement,
• pass scheduling of hot reversing mills,
• the rolling of tapered products by control of roll gap separation,
• the automatic marking of hot strip coils using metal spraying.

During the late 1960s, a mobile computer unit, financed by the Ministry of
Technology, was developed and constructed for initial, on-the-spot investigations
of the dynamics of steel manufacturing processes and subsequent field trials of pro-
posed computer-based automatic control systems.

4.16.2 Energy Reduction
In the mid 1950s there was growing recognition in the industry of the high cost of
energy in the total cost of finished steel products. Initially, a comprehensive analy-
sis was undertaken of the energy required in the various component processes of
ironworks' and steelworks' operations. The design and control of slab reheating
furnaces represented a major activity (See Section 4.9).

Other research activities in the energy sector included:

• fluidised bed studies for heat treatment and the rapid and uniform cooling of
ingot moulds,
• investigation of the application of blast furnace gas as an energy source, par-
ticularly for electricity generation, but also for chemical synthesis of hydrocar-
bons and as a source of energy for fuel cells,
• infrared heating of steel during processing using tungsten filament heaters and
reflective walls,
• the design of oxy-fuel burners,
• high-temperature preheating of scrap prior to electric arc melting. In this study,
a scrap-preheating unit was constructed adjacent to an 8 ton arc furnace at Steel,
Peech and Tozer Ltd. Productivity gains of 20 per cent were demonstrated with
electricity saving of 110 kWh t\(^{-1}\) by preheating the scrap to about 700°C.

4.16.3 Raw Materials Handling
The high cost of maintaining equipment and plant for handling raw materials and
for burden preparation was mainly the consequence of wear on components
exposed to the abrasive action of the raw materials. Particularly vulnerable areas
included chutes at belt conveyor transfer points, belt cleaner scraper blades and
brush bristles, and screening materials. The wear resistance of a wide range of met-
allic, ceramic and plastic materials was assessed on a model scale and at operational sites leading to recommendations for specific applications of these materials.

Following an assessment of the Jenike\(^{12}\) method for the measurement of the flow properties of granular materials, the validity of the technique was studied in relation to bunkerage of iron ore. A 10 ton capacity bunker was specially constructed with variable slope and throat for this purpose. The Jenike method was shown to be valid; provided that an allowance was made for material compaction resulting from the fall of feedstock in the bunker, and that account was taken of the vertical section above the tapered bunker section. The method was subsequently used by BISRA to provide a bunker design service for steelworks.

Other investigations included a study of the degradation of raw materials in bunkers and at belt transfer points. Free fall of material was the major cause of degradation with recommendations made for improvement in design. Scrap handling was also investigated with the need to maximise the scrap holding capacity of charging pans. Vibration was shown to have a beneficial effect with scrap packing density increased by up to 25%.

4.16.4 Structural Engineering
The structural engineering team worked closely with steel producers and other establishments in promoting the design and testing of new or advanced applications for steel. A few examples are described below.

Floor design for steel framed buildings was investigated to determine whether, in situations where concrete floors were supported on steel beams, partial burying of the beam in the concrete floor was structurally acceptable. Potential benefits were anticipated with savings in foundations, superstructure, cladding and services in multi-storey buildings. Laboratory test work indicated that the presence of the beam flange embedded in the concrete slab did not have any marked effect on slab strength. It was concluded that this type of configuration might be suitable for reducing storey heights.

Extensive work in 1966/1967 was aimed at establishing reliable design criteria for the use of the higher yield-strength steels that were then becoming available in structural sections. Codes of practice were formulated and embraced in the British Standard for Steel Girder Bridges. Studies were also undertaken on the possible use of high-tensile steel tendons for the prestressing of mild steel girders in bridge building, and the design and testing of rigid-jointed multi-storey frames. The latter was done in association with the Building Research Station.

An interesting study was undertaken in 1962 on the use of sheet steel in furniture. The BISF Steel Market Development Committee had commissioned this work. A utility stool was made from a single sheet of plastic coated steel by folding and riveting.
4.17 Slag Utilisation and Slagceram

The accumulation of blast furnace slag in various parts of the country was giving concern in the mid 1950s. The use of slag for various industrial purposes had been known for many years; and even now, in North East England, highly wear resistant, recycled slag bricks can be seen used in road guttering and footpaths, and also serrated slag bricks in some older back street roads.

4.17.1 Slag Properties

The basic requirements for building blocks are that the slag must be light and porous, whereas road ballast must be dense. To be able to control its porosity, the Association studied the chemical processes that take place when molten slag is poured. Extensive studies were made into the cause of porosity, and in seeking to improve the quality of air-cooled slags by examination of the mode of crystallisation. One possible cause of excessive porosity is the evolution of dissolved gas while the slag is cooling. Experimental work established the conditions for pick up of nitrogen and a direct relationship was found between the silica content and nitrogen pick-up.

Research into the leaching of sulphur compounds from slags progressed to a stage where it was possible to state how leaching took place and whether or not a slag was likely to be leached to a serious extent. It was shown that the use of slags did not lead to pollution, provided that sufficient attention was paid to drainage from a road, particularly when it was under construction, preventing build up of high concentrations of sulphur species. Considerable attention was given to the effects of adding heat and materials to slag after discharge from the furnace in order to produce value-added structural materials. In the mid 1960s, this work focused on the production of a silica-enriched, fine crystalline material, known as slagceram.

4.17.2 Slagceram

The production economics of slagceram are strongly influenced by the cost of the nucleating agent and the time required for heat-treating the product to give optimum structure and properties. The conditions necessary for the production of good iron oxide nucleated material were identified and, in particular, the importance of the oxidation state of iron ions in the slagceram melt were shown to be of fundamental importance in determining its ability to nucleate. Two types of crystallisation were shown to occur. The first, which occurs with short holding times and/or high carbon additions, depends on the separation of highly reflective droplets from the melt on cooling. The second type, giving dendrites instead of the spherulites of the first type, is dependent on the iron oxide content and the state of oxidation.

The strength of the slag-based glass ceramic material is very high and its abrasion resistance comparable to that of cast basalt. Exposure tests confirmed resistance to marine and industrial atmospheres, while tests with milk and beer showed it to be excellent for applications where there was spillage of liquids, thus offering
good prospects for varied applications. Slagceram can be cast into sand moulds and split moulds to produce a variety of differently shaped products.

Slagceram was a source of great commercial interest in the mid 1960s. By 1968, it was in commercial production for the manufacture of abrasion-resistant pipes and conduit, under licence to a company manufacturing cast basalt products. Other applications being considered at this time were for the manufacture of floor tiles, roof tiles, and railway sleepers. Unfortunately, the material was not sufficiently cost effective at that time as a replacement for existing products.

4.18 Development of Steels

The introduction of increasingly sophisticated techniques of physical metallurgy research in the 1960s provided a new understanding of steel composition and processing schedule requirements to give improved properties to structural steels. Three investigations are summarised as representative of steel development work during the period 1964–1968.

4.18.1 Pearlite-Reduced Steel

The advent of oxygen steelmaking and vacuum degassing processes made it feasible to produce structural steels with low levels of carbon content on a bulk scale. Methods were explored in the laboratory to increase yield strength at these low carbon levels where the yield strength contribution of the carbon itself was at a maximum and the absence of pearlite would assist in achieving good toughness and weldability. The two most feasible ways of increasing yield strength were precipitation hardening with small additions of niobium, titanium and/or vanadium and by grain refinement, the latter also being advantageous from the point of view of toughness. This led to the development of a range of so-called pearlite-reduced structural steels (PRS) with the composition: 0.04–0.1% carbon, 1.2–1.5% manganese, 0.03–0.06% niobium and 0.005–0.025% nitrogen.

The properties achieved in the laboratory (that is, greater than 417 N mm\(^{-2}\) yield stress coupled with an impact transition temperature of -40°C) were reproduced commercially in thin plates and sections. As the section thickness increased, the yield strength decreased and the impact properties deteriorated, but it was still possible to obtain minimum yield points of 355 N mm\(^{-2}\) in plates of thickness up to 32 mm with good impact properties down to a temperature of at least -15°C. Weldability tests and evaluation of such factors as flame cutting, galvanising and machining all gave satisfactory results. The first commercial cast of 100 tons was made in 1964 with the production of light plate and sections and structural hollows reaching 1000 tons per week two years later.

The PRS development served to illustrate the extent to which the properties of low-carbon niobium steels in the as-rolled condition were influenced by rolling schedule and finishing temperature. There was a progressive improvement in both strength and toughness at low finishing temperatures; for optimum toughness, it was necessary to finish-roll at a temperature of 850°C.
4.18.2 Controlled Processing
In the period under review, structural steel technology was advancing rapidly throughout the world with several new standard specifications being issued for high-strength steels. The Association proposed meeting these new specifications by covering the required range of yield strengths with a simple basic steel composition, which could be varied in strength and properties by changes in processing. This concept was pursued in laboratory and industrial trials aimed at improving properties by controlled rolling and by better understanding of the requirements of controlled rolling schedules.

The recrystallisation behaviour of structural steels that contained niobium and/or vanadium, proved to be a major variable in the selection of controlled rolling schedules. Niobium delays the onset of recrystallisation but if rolling schedules are controlled to prevent the formation of a mixed grain structure caused by the retarding effect of the niobium, the potential for controlled rolling is greater than that for vanadium steels. This work demonstrated that it was possible to achieve, at least in plates, all the property requirements of the British Standard comprehensive specification (BS 4360) by controlled rolling, using balanced steels.

4.18.3 Quenching and Tempering
In thin bars controlled-rolled in the laboratory, the yield strength of niobium steel was raised to 463 N mm$^{-2}$ and that of vanadium steel to 540 N mm$^{-2}$. By rapid quenching immediately after controlled rolling, the strengths were raised to 695 N and 772 N mm$^{-2}$ respectively. When the bars were reheated to 950°C before quenching and tempering (Q&T), the resulting yield stress was generally less than that obtained after direct quenching. This confirmed the advantage of direct quenching which at the time (mid 1960s) was becoming available in the United States.

The close control of the quenching operation was an important factor. Although the strength could be realised fairly readily, the toughness requirements were sometimes difficult to obtain. Trials on controlled rolling steels and simulated commercial operations on Q&T steels showed that both strength and toughness were not as readily obtained commercially, but nevertheless the properties obtained were very satisfactory.

4.19 Properties of Steel
The engineering properties of all grades of steel become more exacting as competitive pressures increase. This is a continuous process but commercial demands were particularly acute in the 1960s and a major proportion of metallurgy research effort was focussed on improving the mechanical properties of plain carbon, low alloy and high alloy steels. The influence of such factors as grain size, precipitation and solid solution hardening, mechanical deformation and transformation kinetics was examined. Some specific aspects of this work are illustrated below.
4.19.1 Thermomechanical Treatment

Exploratory work in 1963 showed that considerable grain refinement with a resulting improvement in mechanical properties could be obtained in low-carbon steel sheet by quenching the steel to an intermediate temperature immediately after the finish-rolling pass during hot processing. Subsequent laboratory trials determined the importance of rolling temperature, amount of reduction, quenching temperature and time held at temperature. This thermomechanical treatment (TMT) increased yield strengths while retaining adequate ductility for forming operations. Early tests established that a 0.5% manganese steel subject to TMT gave a yield strength after treatment of 381–510 N mm\(^{-2}\) compared with 324–340 N mm\(^{-2}\) for conventionally rolled material. Strength values for 1.5% manganese steels were also increased from 378–502 N mm\(^{-2}\). Laboratory work was followed by commercial production of casts for customers' evaluation. The changes necessary on the hot mill were to lower the finish temperature and improve the run-out cooling system to accelerate cooling to the coiling temperature. Product properties in terms of strength, ductility and weldability were very encouraging.

In related studies, the process known as ausforming successfully increased both the strength and ductility of low- and medium-alloy steels. The process also had an advantageous effect on fracture toughness. In this work, TMT was applied mainly to steel in which the allotropic change was from austenite to martensite during quenching. The attractive combinations of the strength and toughness obtained suggested beneficial effects where the product of transformation was other than martensite.

With ferritic steels, a high temperature form of TMT was used effectively. Reduction in the finish rolling temperature of low carbon ferritic steel containing manganese and niobium can have a dramatic effect on the yield strength where the finishing temperature is below 750°C. The high temperature TMT of simple low alloy steels, in fact, was shown to have characteristics similar to that of low temperature treatment of low alloy steels. The effect of deformation during the transformation to pearlite of low alloy steel did not result in any increase in tensile strength over conventionally treated material but did show a marked increase in ductility and toughness. This effect, together with the increase in 0.1% proof stress also achieved, provided a remarkable combination of properties for relatively cheap alloy steel processed in a simple way.

In later work, attention was concentrated on improving toughness at a given level of strength. One of the most important applications was in tool steels where relatively low alloyed steels could be hardened up to strength levels usually associated with high alloyed grades while retaining a high degree of toughness. Compositions within the range 0.3–0.6% carbon with 3–5% chromium and additions of molybdenum, vanadium and tungsten could replace high-speed steels for applications such as trim dies and punches. A co-operative programme with tool steel producers and users to exploit these findings was underway at the time when the British Steel Corporation was formed.

Deformation during isothermal transformation (isoforming) was also studied
and shown to be particularly effective for pearlitic steels. In this case, toughness was improved far more than strength. In an extension of this work, elevated temperature deformation of pearlite followed by a simple aging treatment gave a fine sub-grain structure similar to that observed in isoforming, with consequent improvement in proof stress and toughness. The strict control required in the isoforming process was not required and this alternative approach was considered likely to be more acceptable commercially.

4.19.2 Engineering Properties

Many properties have to be considered in selecting steels for engineering purposes with particular combinations required for different applications. The Association's research programme covered a wide field of activities to provide information that would serve as a realistic basis for the preparation of steel specifications and lead to better design codes, and hence more efficient use of steel properties. The properties examined by BISRA through the activities of the Metallurgy Committees included tensile and creep rupture at elevated temperature, fracture toughness under elastic and elastic-plastic conditions, fatigue, machinability, corrosion and stress corrosion resistance, weldability and hardenability.

To consider one of these properties, the value of impact transition temperature as a measure of toughness had already been closely examined, particularly in relation to high strength steels. New concepts of linear elastic-fracture mechanics had been developed in the United States and their application in the UK was studied both by BISRA and in the laboratories of member firms. The technique of fracture toughness was not easy to acquire and the Association played a central role in assisting member firms to equip and train their staff. Thus, in the late 1960s, the application of fracture mechanics to the assessment of the resistance of steels to crack propagation and fracture was finding increasing acceptance. By adopting this approach, it was possible to develop valid tests for assessing toughness in steels for a wide range of strength levels.

In testing high-strength steels, one requirement was the development of a short crack in the test piece prior to raising the load to fracture the specimen. Precise control was necessary at all stages in the test procedure. To meet these requirements electro-hydraulic equipment for assessment of toughness was installed in the Sheffield Group Laboratories. The equipment independently operated three load frames of different load capacities. Each test piece could be subjected to cyclic loading of a chosen waveform and frequency prior to application of a steadily increasing load to fracture the test piece. The equipment was shown to be particularly suitable for studies of crack growth processes. Test pieces or components were subject to environmental conditions and stress cycles, which simulated specific service conditions. This test facility is shown in Fig. 32 and exemplifies the level of sophistication of physical metallurgy techniques for engineering property assessment at the end of the 1960s.
4.19.3 International Co-operation
With the development of improved steels to meet more exacting engineering conditions, much more information was needed about properties under a variety of conditions. The British Steelmakers' Creep Committee, with the aid of BISRA staff, was asked to undertake responsibility for the collection and analysis of elevated temperature, tensile and long-term creep and rupture data submitted by member countries of the International Standards Organisation (ISO). The results of this analysis were accepted by the ISO as the basis for obtaining agreement on property levels for pressure vessels specifications. This exercise covered carbon and alloy grades and dealt with creep rupture data and proof stress data from several thousand casts from fourteen countries. The advantages of collaborative data collection and analysis were clearly demonstrated and inspired similar activities in the fields of weldability and fracture toughness.

4.20 Corrosion Prevention
Co-operative research on the causes and prevention of corrosion of iron and steel started in 1928 with the formation of the Joint BISF and ISI Corrosion Committee, chaired by Dr W. H. Hatfield. The work of this Committee and its subcommittees is featured in the series of Special Reports that was issued by the Iron and Steel Institute during the period 1931–1944.5

Corrosion research seeks an understanding of corrosion mechanisms and means for prevention or minimisation by material choice, methods of protection and con-
ditions of use. These studies are undertaken in association with laboratory corrosion tests, and the examination of corrosion of steel components in use. Long-term exposure trials were an important part of this work despite changing emphasis in the 1960s towards more advanced laboratory techniques. BISRA exposure sites provided a wide range of differing atmospheric conditions across Britain. Some of the varied work on corrosion at the London Group Laboratories during the mid 1960s is summarised here.

Knowledge of the part played by contaminants in the rusting process is an important factor in preventing steelwork corrosion. This was endorsed by findings in which as much as 20% of the rust retained on mild steel after exposure for some months consisted of contaminants of various kinds. After wire brushing, about 90% of a harmful soluble sulphate was found in the rust layer still adhering to the steel. This sulphate is not removed by heating nor is it readily washed away.

Raft-immersion tests to discover the best method for preparing ships’ bottoms for painting confirmed the value of descaling the plates, provided that suitable steps were taken to overcome the lack of adhesion that sometimes occurred between freshly descaled plate and the paint scheme. The use of a pre-treatment primer was one of the best solutions.

In order to advise shipbuilders on the most effective use of blast-cleaned steel, a series of blast-cleaned panels cut from ships’ plate were prepared and painted and then immersed in the sea to check the effect on the performance of the finishing paints of the alternative surface preparations and priming paints applied. Other test plates were exposed in a shipyard to simulate the weathering that the hull receives during shipbuilding before the final paint scheme is applied.

Weathering steels, such as Cor-Ten, form protective rust that eventually reduces corrosion to negligible proportions. One objection to their use is that rainwater flowing off the steel can stain concrete while the rust layer is building up. In situations where this effect could not be avoided through better design, staining was easily prevented by treating the concrete, for example, with a chlorinated rubber substance. The local use of a non-stainable material, such as glass, glazed brick, PVC or painted steel, provided another solution.

The surface pitting and rust staining of some stainless steels in certain atmospheres, while not of mechanical significance, detracts from their appearance and may restrict their use in architecture. Six years of exposure of various grades of stainless steel in marine and industrial atmospheres indicated that an 18-10-3 Cr-Ni-Mo steel was suitable for cladding buildings in all such environments. Less highly alloyed grades could also be used outdoors in industrial areas provided that routine maintenance cleaning was adequate.

The effect of non-metallic inclusions on pitting was studied with a view to improving the competitiveness of stainless steels in cladding applications. Specimens with elevated contents of various inclusions were examined after exposure in the atmosphere for one year. Scanning electron microscopy revealed the crystallographic dependence of pitting of alloy steel in the atmosphere and this is shown in Fig. 33.
For the effective use of zinc-coated steel, it is important to know how much damage the coating can endure without losing its protective ability. Tests were undertaken in which zinc-coated products were deliberately damaged and then exposed at various test sites. The simulated damage consisted of grooves of different widths milled through the coating to expose the steel. The coating successfully protected the steel (after two years’ exposure) at gaps up to 1.6 mm wide on top horizontal faces at the severest industrial site, and up to 3.2 mm wide at other angles of exposure and at other sites.

In 1968, the results of trials lasting up to fifteen years on the corrosion of buried pipes indicated that the industrial protective coatings then in use would prevent serious corrosion, provided that pipes were not damaged during transport and laying. Since it was usual to apply cathodic protection as well as coatings, a good modern practice would reduce the danger of soil corrosion of pipelines to negligible proportions. With bare cast iron and mild steel pipes the corrosion rates were quite low for natural environments, but the pitting rate was relatively high. Good protection was given by coal-tar pitch and bitumen coatings, and especially by a 6 mm thick bitumen sheathing. Hot-dip galvanised coatings also behaved well, as did an acid-resistant vitreous enamel.

The technical services that were provided by the Corrosion Advice Bureau are briefly mentioned in Section 4.24.

4.21 Measurement and Analysis

The development of measurement technology was an essential feature of virtually all the Association’s research activities, with projects often hampered by lack of suitable instrumentation or by unreliability of components still at an early stage of development. Many of these developments were highly innovative and with hindsight ‘ahead of their time’. This development work is illustrated by a number of project activities.
4.21.1 Surface Inspection
Automatic surface inspection both on- and off-line presents formidable difficulties. Several techniques were investigated in attempts to develop viable methods. For tinplate, a closed-circuit TV system and optical image arrestment system was tested on an electrolytic tinning line. Performance was good although some defect types were not adequately recognisable. For cold strip, flash photography was tested: fast-moving strip was successfully photographed on a re-coiling line using a stroboscope and 16 mm cine camera. In both cases, good image arrestment was demonstrated, even at the highest line speeds. Design specifications were drawn up for industrial installations but successful implementation of optical systems of the type used in this work were delayed until the much later development of high-power computing capable of distinguishing the wide variety of defect types.

4.21.2 Measurement of Dimension
Optical techniques were used to provide dimensional control during the mechanical working of semi-finished products. A gauge designed to measure the diameter of hot bar and rod was carried to the prototype stage and the design licensed to a manufacturer. Figure 34 shows the measuring head of a prototype gauge undergoing trials in the finishing stand in a bar mill. The bar was back-illuminated to eliminate the difficulties encountered in using the self-luminosity of the hot bar. A focused shadow image of the bar was formed in the plane of a narrow scanning slit. The light passing through the slit fell on a photocell and generated a substantially square wave signal; the width of the square wave was measured by using a digital timer. The prototype had a twin head unit to measure vertical and horizontal bar diameters over a range of 5–38 mm. It successfully met the specification require-

![Fig. 34 Measuring head of an optical bar gauge on a mill finishing stand.](image-url)
ments of ±0.05 mm accuracy with a response time of 10 ms. Accuracy was unaffected by bar shake and mill vibration.

Another requirement for dimensional control was also met by the use of optical techniques. A width meter was developed to help tinplate works in the precision measurement of strip width. The image of one edge of the strip was optically transposed to appear close to the other edge. The gap between the edge of the transposed image and the other real edge was measured by a photoelectric cell. A prototype of this gauge was installed on a trimming line in South Wales.

4.21.3 Measurement of Shape
Sheet is commonly regarded as having poor shape if it displays a wavy appearance when laid on a flat surface with zero tension. This manifestation of shape is associated with a pattern of internal stresses in the sheet. Under high tension, e.g. on the mill, it appears flat and the stress pattern is modified. Tensile stress affects magnetic permeability (the magneto elastic effect) and a shape sensor was developed that was responsive to change in permeability.

Cold-rolled sheets were subjected to variable longitudinal tension in a test-rig and a probe responsive to permeability changes was traversed across the width. Above a critical tension (the tension at which the strip appears flat), measurement sensor records were shown to be in good agreement with the transverse profile of longitudinal stress in the sheet. Sensitivity (change in permeability per unit change in stress), as well as magnetic directionality (ratio of longitudinal to transverse permeability), varied considerably for steels of different composition, but were reasonably constant over the width of any one grade and gauge. Works trials were set in progress at BSC's Orb Works on a four-high single-strand reversing mill used mainly for rolling electrical steels.

4.21.4 On-Line Analysis
The use of radioisotopes to excite X-ray fluorescence was the principle employed in OLIVER, a unit constructed for the semi-continuous analysis of sinter-feed mixtures. A unit was installed at BSC's Appleby-Frodingham Works to investigate the feasibility of continuous data logging of lime-silica ratio to enable feedback control of preparation of the sinter feed. The trials revealed the extent of variability of sinter feed and the data was used to improve control of both the sintering process and blast furnace operation. The later enhancement of iron-ore bedding techniques led to improved standards of control of sinter-feed variability.

Developments in the process control of oxygen converter steelmaking stimulated the further investigation of sensors and methods for the direct in situ analysis of molten steel. As part of this work, the electrochemical cell technique for measurement of the oxygen activity of molten steel was tested and shown to be successful on an experimental scale. Industrial application was hampered by the susceptibility of the solid electrolyte thimble to thermal shock. This was resolved by careful choice of material source with stabilised zirconia in the form of a closed sheath, impermeable to gases, being used.
Trials were also conducted to test the feasibility of monitoring the full composition of steel continuously by obtaining a powder sample, through a lance, which could be transported outside the vessel to a plasma jet for spectrographic excitation. The prototype probe used for in-bath sampling is shown in Fig. 35. Although demonstrated as being feasible, the engineering difficulties of maintaining analytical conditions at a standard necessary to obtain accurate results precluded its adoption. More than twenty years elapsed before the direct spectrographic analysis of molten steel was shown to be feasible using lasers.

4.21.5 Analysis Instrumentation
BISRA played a leading role in the development and application of the wide range of instrumental methods of chemical analysis that were introduced during the late
1950s and early 1960s. The application of new measurement principles was explored on behalf of the industry, for example, atomic absorption spectroscopy for trace element determination, and automatic spectrophotometric analysis for multiple-element determinations. This was at a time when direct reading spectroscopy had not been sufficiently developed to take on the workload of the works' chemical laboratory.

Novel techniques employing emission spectrographic and X-ray fluorescence measurement were developed for ores and slags to replace tedious chemical procedures, with the work emphasising the need for stringency of sample preparation when handling oxide materials. Other techniques such as mass spectrometry and neutron activation were explored; and an examination made of direct electron-excitation spectrometry demonstrated its suitability for determination of low-atomic number elements.

Work on instrument development included the Dynacarb for the rapid determination of carbon based on the dynamic infrared measurement of carbon dioxide evolved during high-speed combustion of a sample of steel. This principle was later widely adopted by manufacturers and forms the basis of present-day commercial instrumentation.

4.21.6 Collaborative Analytical Research

The strong tradition in the industry for collaborative study in the development of analytical procedures dates back to the work of the Iron and Steel Industrial Research Council. At one time there were more than twenty subcommittees and working groups under the aegis of the BISRA Chemical Analysis Committee developing new procedures to meet ever-tightening steel specifications and promoting instrumental methods to replace traditional procedures. The organisation of this complex structure was the responsibility of the Association.

4.22 Fundamentals of Ironmaking and Steelmaking

Studies of the physical chemistry of ironmaking and steelmaking are essential to understand processes and improve their efficiency. The fundamental work on the thermodynamics and kinetics of iron and steelmaking reactions, initially under the leadership of Dr F. D. Richardson and later Dr J. Pearson, is well known and is possibly one of the most significant features of the Association's early research investigations. The objective was to survey existing knowledge, which at that time was scarce and rather unreliable, and to develop an understandable method of presenting the data.

Theoretical work began with studies of the iron–carbon, oxygen and sulphur systems, and the plotting of free energy changes for the formation of various compounds against temperature with particular reference to reduction processes in the blast furnace. Other studies investigated the possibility of scavenging hydrogen from steel by the addition of stable-hydride forming elements, the addition of vanadium and chromium to rimming steels to eliminate strain age hardening and the
equilibrium between slags and gases containing sulphur. Some of the many experimental studies made during the late 1940s and early 1950s at Battersea and at Imperial College are listed below:

- Thermodynamics of sulphur in iron and slags, and the effects of carbon, oxygen and other elements. Activities of iron and sulphur in the molten binary iron–sulphur system were calculated as part of this study.
- Thermodynamics of phosphorus in liquid iron and of phosphates. Both oxygen and phosphorus dissolved in liquid iron reduce each other’s activity coefficients although, at the concentrations usually encountered in steelmaking, the effect can usually be neglected. The change in activity is related to the free energy of formation, and thus the stability, of the compound likely to be formed from them.
- Interaction of carbon and sulphur to explain the mutual raising of the activity coefficients of these two elements when dissolved in liquid iron.
- Thermodynamics of sulphur in solid iron and steel. The presence of manganese reduces the solubility of sulphur with the results explaining why the hot-shortness of iron containing sulphur may be overcome by the addition of sufficient manganese.
- Determination of the constitution of molten slags by electrical conductivity and transport measurement; also the determination of heats of formation and heat contents of various slag compounds.
- Thermodynamics of iron oxide bearing slags in which melts were equilibrated with CO/CO$_2$ mixtures. Increasing amounts of silica and/or phosphorus pentoxide decrease the ferric/ferrous iron ratios appreciably, phosphorus pentoxide being more effective than silica. This work enabled the construction of curves relating the ferric/ferrous ratio to silica and phosphorus pentoxide concentrations for various CO/CO$_2$ ratios in the range 75.0–0.1 where slags are in equilibrium with liquid iron.
- Surface processes in the movement of hydrogen into and out of solid iron and steel. The passage of hydrogen from the gaseous state into solid iron involves preliminary surface adsorption, which is followed by a slower absorption; in fact, the study was based on the free energies of adsorption of hydrogen, carbon monoxide, nitrogen and oxygen on films of iron.
- The movement of sulphur between gases and liquid iron via a steelmaking slag. This study involved the measurement and validation of the sulphur capacities of CaO.SiO$_2$–MgO.SiO$_2$ mixtures.

More than sixty papers were published during the 1950s, mainly in the Journal of the Iron and Steel Institute, which included classic surveys of activity coefficients and free energies of formation of constituents. Together these papers provided an invaluable repository of data for later research at BISRA and elsewhere. In the steelmaking area, this culminated in the publication in 1996 of Dr E. T. Turkdogan’s book, Fundamentals of Steelmaking. The author of this book was Head of Physical Chemistry at Battersea from 1950 to 1959.
Fundamental studies continued into the 1960s, but were increasingly directed towards specific problem areas. These included refractory use of carbon in the blast furnace, leaching of compounds from blast furnace slag, mechanism of iron-oxide fume formation, vacuum decarburisation of steel, and pick-up sulphur from gases during the melting and refining of steel.

4.23 Operational Research

Sir Charles Goodeve introduced the application of the scientific method to steelworks' operations and to human factors when BISRA was constituted. At the time, it was a relatively new concept in the steel industry. Of the many diverse activities in this area, three early developments have been selected to illustrate the potential of operational and organisational research.

4.23.1 Reliability of Steelworks' Plant

With the increasing degree of automation in the early 1960s, it was becoming important to establish in precise terms the ability of steelworks equipment to operate at specific levels of performance for a specified time. At that time, over half the labour force in the industry was concerned with maintenance and considerable sums were tied up in spares inventories. A method of measuring plant downtime was developed to provide data for a mathematical model for predicting plant behaviour and the effect of reliability on overall efficiency. Operational research was concentrated on three primary mills and served to highlight the effect of changes in maintenance and operational policies on plant reliability. It appeared that saving time by reduction in planned maintenance could more than offset any increase in time lost from an increase in plant failures. In one case, the scheduled operating time of the mill was increased from seventeen to twenty shifts per week resulting in a 36% increase in mill output with about half of this improvement attributable to a decrease in weekend maintenance, freeing extra shifts for production. The essential aim of this work on plant reliability was to develop methods to help management decide how much should be spent on maintenance, and show how costs should be monitored and controlled.

4.23.2 The Man-Machine Interface

The role of the operator in highly automated systems was the subject of a number of studies in the 1960s aimed at identifying the problems likely to arise in the introduction of an on-line process control computer. This work emphasised the need for ergonomic analysis of the operation of a new plant at the design stage, so as to specify the division of work between man and machine, the design and layout of controls and displays, and how best to cater for breakdown and emergency situations. An important objective was to detail the job of the operator as the basis for selection and training. This was achieved by simulation exercises to evaluate the effect of the information flow between operator and computer on the overall control of the particular process. In one study, a novel touch-wire visual system was evalu-
ated to determine how well operators could use such a system to enter information into a central computer. A mobile computer unit was commissioned in 1969 for speeding up the development and validation of new control systems of this type (see Section 4.16).

4.23.3 Accident Reduction
Research aimed at reducing accidents began by establishing the main causes of injury as environmental, physiological, psychological and social. One of the first investigations was to discover why workers resisted the use of personal safety equipment, such as protective footwear. This brought to light some of the often-intangible influences, such as individual psychology and social environment, on the wearing of safety boots and led to recommendations for increased acceptance, and later to the introduction of boots of improved design. In another early study, it was shown that the team leader influenced significantly the number of accidents occurring to men working as a team. The effectiveness of accident posters was a controversial issue at the time; but a well-designed poster could be effective weapon against accidents especially where the safety message was clearly seen by the worker to be appropriate to him.

In 1957, a method was introduced for interpreting work’s accident frequency records to take account of statistical fluctuations, in a manner analogous to quality control charts used by inspection departments. This type of method became well established as a method of accident control in industrial processes. Later studies pointed to the importance of staff selection and training in relation to accidental injury and also cast doubt on the validity of accident frequency rate as a measure of safety and changes in work’s safety procedures. In a related exercise, damage control schemes were proposed to highlight all accidents, not only to workers but also to plant, machinery and materials, so as throw new light on the causes of accidents, thereby contributing to their elimination. In 1965, three companies introduced schemes of this type on an experimental basis.

4.24 Technical Services
While the Association’s research staff assisted members in solving special problems, more general advice and assistance was provided both for members and others in industry by the Steel User Service and the Corrosion Advice Bureau. Personal contact with industry was an important part of the remit of staff with frequent visits paid to firms not only to deal with specific enquiries (Fig. 36), but also for liaison purposes and promotion of BISRA research.

4.24.1 Steel User Service
The extensive industrial experience of the staff of the Steel User Section ensured a sound, practical approach to such problems as steel selection, suitable heat treatments, information on mechanical properties, interpretation of specifications, and analyses and investigations into causes of failure. A typical example was an
enquiry from a company anxious to produce cutting blades to match the quality of a foreign product. Metallurgical examination revealed small differences between the blades, so a new heat treatment cycle was devised to produce a blade of comparable quality. Other enquiries in a typical year included requests for information on the use of aluminium as a deoxidant, selection of heat treatments, high temperature testing of steel, failure of feed-water pipes and pump shafts, protection of steel linings in hydro-electric scheme tunnels, and expected life of metal fixing systems.

Between two and three thousand enquiries were received each year by the Steel User Service in the 1960s. A high proportion of these concerned steel specifications and properties. It was decided to compile all information on the British Standard range of 'En' steels in one publication, subsequently published in three volumes. Some of the more complex requests called for laboratory experimentation and resulted in extended projects. Ad hoc investigations for steel users can be illustrated by three related projects.

- The effects of fuel oils with differing sulphur contents on steel surfaces during heating for forging and rolling. The amounts and adhesion of scale, sulphur pick-up and extent of decarburisation were measured and a guidance report issued on the selection of fuel oils.
- Factors affecting decarburisation in billet reheating furnaces in rod and bar mills. A working group of thirteen re-rolling companies was formed to co-operate with
the Steel User Service with the laboratory study providing data for furnace modification, thus enabling a number of companies to improve the quality of their rolled products (Fig. 37).

- Metallurgical implications of the rapid heating of billets. A jet impingement technique was developed, which offered substantial benefits, in the form of lower decarburisation and scale losses. Investigations were also made to assess the degree of protection afforded to the quality of billets during reheating by various surface coatings.

4.24.2 Corrosion Advice Bureau
The Bureau’s main task was to solve specific problems and advice on corrosion protection with enquiries coming from steel users in many industries. In the late 1960s, over one thousand separate questions were dealt with covering many aspects of corrosion. Another important task was that of publicising methods of preventing corrosion, and a series of five Corrosion Prevention Booklets was published by BISRA in the mid 1960s.15

Laboratory investigations were made to determine the cause of failure with typical examples involving the examination of building components, corroded reinforcing bars, galvanised roofing sheet, steel springs, industrial radiators and crevice corrosion in stainless steels. Enquiries in a typical year included requests for information on the white rusting of galvanised sheet during transit, protection of mild

Fig. 37 Steel User Service investigation of billet decarburisation in reheating furnaces.
steel acoustic tiles, and surface preparation and protection of structures. Sponsored work included stress-corrosion tests on stainless steels, the application of various steels in central heating systems, the protection of stainless steel tanks, paint coatings for bridges and tests on proprietary coatings and processes.

One major sponsored study involved extensive tests on the painting of metal-sprayed structural steel. In 1960, doubts emerged about the general efficiency of sprayed metal covered by paint. A long-term project was launched to establish the conditions under which these systems could satisfactorily protect steels for specified periods. Exposure tests at four sites in the UK and in West Africa provided valuable data; an account of the work was later published.

5. TRANSFER OF BISRA IN 1968 TO BSC

The British Iron and Steel Federation was dissolved in October 1967 following the nationalisation of the greater part of the steel industry. Control of BISRA was transferred to the British Steel Corporation (BSC) in March 1968. While legally retaining the name British Iron and Steel Research Association, it became known as The Inter-Group Laboratories of the British Steel Corporation, whilst retaining the prefix BISRA. The Corporation appointed members of its Senior Technical Committee to be the Board of Management under the chairmanship of Mr P. A. Matthews, Board Member for Research and Development. In the financial year 1968/1969, the last year in which Annual Accounts were issued for BISRA, the expenditure on research was £2.4 million, of which the British Steel Corporation financed £1.9 million, the balance coming from private industry and other sources.

Sir Charles Goodeve retired as Director in February 1969 but remained involved in occupational research, a science that he had advocated throughout the war years and during his time at BISRA. He was highly regarded by all in the steel industry and especially by his former staff, so many remember him with respect and affection. Dr Robert Barnes, previously head of the Metallurgy Department of the Atomic Energy Research Department at Harwell, was appointed Director to succeed Sir Charles Goodeve. Following the transfer to the British Steel Corporation, BISRA staff had full access to the research programmes of the Groups and Divisions providing the opportunity for closer collaboration in works trials and in the cost benefit analysis of projects.

In 1971, the Divisional and BISRA research and development programmes were brought together into a single integrated programme allowing rationalisation and prioritisation of activities with defined centres of excellence in selected areas. A Research Committee chaired by Dr Barnes, who by then had been appointed Director of Research and Development for the Corporation, was formed with the remit: 'To keep under review and co-ordinate the research and development work of the Divisional and Corporate Laboratories'.

Membership of the Research Committee comprised Heads of Research of the Corporation's Divisions: Mr J. McKenzie, General Steels; Dr K. J. Irvine, Special
Steels; Mr F. H. Smith, Strip Mills; Mr G. J. McEwan, Tubes; Mr F. H. Needham, Constructional Engineering; and Mr H. Markham, Chemicals. Dr E. A. Calnan, who had been appointed Head of the Corporate Laboratories of BISRA following a short period when Dr J. H. Chesters was Director, was also a member. Eight Technical Committees were formed to support the Research Committee: Ironmaking, Steelmaking, Properties of Steel, Quality, Corrosion and Protection, Instrumentation, Control Engineering, and Energy. A joint committee was formed with the British Iron and Steel Independent Producers Association to oversee technical collaboration with the private sector of the industry. This Technical and Research Collaboration Committee was subsequently broadened to include representatives from the Metallurgical Plantmakers Federation and other bodies, and certain specialist committees were appointed, such as the Chemists' Committee.

In September 1972, a new structure of three Corporate Laboratories was introduced with some integration between the former BISRA laboratories and the laboratories of the Corporation’s Groups and Divisions. These were the Corporate Advanced Process Laboratories at Middlesbrough, headed by Dr F. Fitzgerald; the Corporate Development Laboratories at Sheffield, headed by Dr R. L. Craik; and the Corporate Engineering Laboratories at Battersea, headed by Dr J. G. Wistreich. Integration of divisional and corporate research was completed in 1976 with the formation of six regional laboratories: Teesside, Sheffield, Welsh, Scottish, Shotwick and Battersea. Further rationalisation of resources took place within the Corporation in the late 1970s and early 1980s. Despite this contraction of activities, the technical contribution of the research and development function remained strong, as can be seen in Steelresearch, a periodic publication that was instituted by Dr Barnes in 1973. Thirteen issues of Steelresearch were published in the period up to 1990, each with fifteen to twenty articles designed to provide a ‘shop window’ on research in BSC; each issue contained a list of published research papers. Of the former BISRA laboratories, only the Teesside Laboratories at Middlesbrough survived the century as part of the much larger Teesside Technology Centre, now part of the Corus Group; but ex-BISRA members of staff were to contribute strongly to the re-shaping of steel research in the British Steel Corporation and subsequently in the privatised British Steel plc.

6. ACKNOWLEDGEMENTS

In compiling this chapter, the authors have drawn on archival material and BISRA Annual Reports and for this they are grateful for the support of British Steel plc, whose forerunner, the British Steel Corporation, took control of the British Iron and Steel Research Association in 1968. British Steel plc is now part of the Corus Group plc. Thanks are due to Dr R. B. Smith, while Research Director of the Teesside Technology Centre, for his help and encouragement, and to library staff and others at the Centre for their assistance.

The authors acknowledge the creativity and technical contribution of former col-
lewages and all staff who worked in the BISRA laboratories. The account of research activities presented here cannot do justice to all their efforts. The authors' regret is that it has not been possible to cover a wider and more comprehensive range of activities from the many hundreds of research projects undertaken over a period of twenty-five years. It is recognised that some projects 'close to the hearts' of many former staff of BISRA have not been covered. In addition, the support of member companies of BISRA, and the guidance of the Technical Committees and other industry experts are acknowledged as well as the assistance of plant management in making possible the testing and implementation of research developments. The BISRA research programme represented only a part of the industry's research and development efforts during the period 1944–1968. Tribute is paid to the staff of the central laboratories of member firms for their own research endeavours during these years, and for their work in striving to benefit the profitability of the industry.

To those in the industry who regarded BISRA as an irritant, the authors make no apology. They hope that at least some of the oysters live on!

7. REFERENCES


CHAPTER 5

Twenty-First Century Ironmaking and Steelmaking

R. B. Smith and M. G. Sexton

1. INTRODUCTION

World steel production by region since 1950 is shown in Fig. 1. Growth in production since around 1970 has been relatively slow and this is forecast to continue into the twenty-first century. It is apparent there has been little or no growth in the mature markets of Western Europe, North America and Japan. The main growth has been, and will continue to be, in Asia (now resuming after the recent crisis) and to a lesser degree the rest of the world.

World steel production by process is shown in Fig. 2. Major developments in process technology are apparent with the shift from open hearth to oxygen steel-making and more recently an increasing emphasis on electric arc furnace production with the majority of current new steelmaking investment being in this area. This is parallel with recent growth in direct reduction, although it currently only makes up to around 5% of world production, whilst smelting reduction production is only up to 2 million tonnes per annum (Mtpa) (around 9.3%).

![Fig. 1 World steel production 1950–1998.](image-url)
It is clear that the timescale for the development of new process technology is measured in decades owing to slow growth, long life of existing plant and the low variable cost of current blast furnace and BOS plant. The latter point is crucial as it is not economically viable to replace existing BF/BOS plant with the new technologies such as electric arc furnaces, direct reduction or smelting reduction until the plant reaches the end of its life or several rebuilds occur simultaneously (e.g. BF and Coke Ovens). Thus the strategy in areas where there is little or no growth is to maximise the profitability and competitiveness of existing plants, prior to replacing them at the end of their life either by deploying new primary process technology or by cost-effective rebuilds. In areas where there are growth opportunities, there is a wide range of process technologies available, which can be tailored to match local market demand, feedstock and energy availability.

In this chapter a brief overview of the types of developments taking place in existing plants to maximise their competitiveness is given, followed by a more comprehensive review of new process technology in ironmaking, steelmaking and casting. Sustainability is a key requirement at the turn of the century and an overview of how the steel industry is responding to this challenge is provided, together with an overview of how the new process technologies enhance sustainability in the future. Finally, general guidelines are provided on the choice of process route in the future.

2. DEVELOPMENTS TO EXISTING PLANT

As a result of previous investment programmes, the vast majority of blast furnace/BOS plants in mature markets, such as Western Europe, have good quality process plant with many years of life left in them. Thus, as indicated previously, the
Forward strategy is to maximise the profitability of these plants by producing higher value products and to reduce the cost by operational improvements and extending plant life. This strategy is pursued by both improving the capability of existing equipment by, for example, improved measurement and control, and by selective investment in new capital equipment. Examples of developments in ironmaking, steelmaking and casting are given below although the strategy clearly extends into rolling, e.g. new section shapes, such as the asymmetric beam, which is part of the slimdek system (see Fig. 3), and coating operations, e.g. production of galvanneal strip for automotive customers and organically coated strip for domestic and construction applications.

2.1 Ironmaking

The major emphasis in ironmaking has, and will continue to be, cost reduction, life extension and improvement in environmental performance. Cost reduction has been achieved by productivity increases owing to operational improvements and also by reducing the number of furnaces, removing the older, most inefficient units (Fig. 4). Equivalent coke rate in the furnace has reduced significantly, giving cost and environmental benefits. Also injection technology has developed with coal injection now installed on most furnaces. Developments in other injection technology, such as oil, natural gas, fine ore, waste oxides and possibly plastics, will also continue to reduce fuel rates further and to balance the materials loading on the blast furnace. Charging pre-reduced material to the blast furnace (i.e. DRI or scrap) can also significantly increase productivity and could play an increasingly important role in future strategies.

Maximising asset life to defer expenditure on plant replacement is also key to maintaining competitive plants. Developments in cokemaking on coal blend selection, control and monitoring, improved maintenance and inspection are geared to
achieving a forty year campaign life on current coke oven batteries. To replace coke ovens lower cost technologies, such as the Sun non-recovery ovens as installed at Inland Steel and the Jumbo Coke Oven being developed in Germany, can be applied as alternatives to rebuilding end-of-life ovens or deploying the new process technologies described below.

The emphasis being placed on extending plant life as much as possible has led to a levelling off in blast furnace productivity over the last six years or so in the UK plants of Corus (Fig. 4). As an example, Redcar blast furnace has reduced its daily production capacity from over 10 ktpd to 9 ktpd. Some key developments in the ironmaking area on life extension are:

- stability task teams,
- long life hearth group,
- plant condition monitoring,
- shell cooling improvements,
- liquid management systems using EMFs
- operator guidance systems for improved operation and reduced fuel rates.

However, in the future extended plant lives will also be achieved by further improvements in hearth design and the use of copper staves. Other key blast furnace developments are advanced probes and instrumentation, process control and expert systems (Fig. 5). Overall there is still scope for significant further developments in blast furnace ironmaking to achieve further reductions in cost and to respond to future challenges.

2.2 Steelmaking

In BOS steelmaking, cost reduction and life extension have and will continue to be
important development areas. However, to exemplify recent developments and trends into the next century the important area of improved product quality is presented. Table 1 gives typical steel quality improvements that have been achieved over the last twenty years. These improvements have been achieved by improved control of BOS operations by using a sub lance, automated blowing, advanced control models and a variety of techniques to minimise slag carryover. More important, however, has been the rapid growth in secondary steelmaking with the provision of ladle treatment stations, RH degassers and reheating by either ladle furnaces or CAS/OB. Figure 6 shows the growth in these facilities at Teesside Works between 1972 and 1995. Selective investment in these facilities continue and, for example, a tank degasser was recently installed at Teesside to enable production of advanced linepipe steels (Fig. 7).

Future development in improved product quality will be targeted to get the best out of existing equipment and, where appropriate, installing new secondary steelmaking equipment. To achieve the former, developments in computing power, software and advanced sensors will provide even more precise control to achieve tighter control and improve the capability to make new grades. The use of manufacturing execution systems, export systems, neural networks, case-based reasoning, etc., will all play increasingly important roles in plant control to achieve 'right every time' at minimum cost.

Table 1  Typical steel quality improvements.

<table>
<thead>
<tr>
<th></th>
<th>C, %</th>
<th>Mn, %</th>
<th>Si, %</th>
<th>S, %</th>
<th>P, %</th>
<th>N, ppm</th>
<th>H, ppm</th>
<th>O (total), ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical</td>
<td>0.030</td>
<td>0.20</td>
<td>0.02</td>
<td>0.005</td>
<td>0.015</td>
<td>60</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>Current</td>
<td>&lt;0.002</td>
<td>&lt;0.050</td>
<td>&lt;0.010</td>
<td>&lt;0.001</td>
<td>&lt;0.008</td>
<td>&lt;25</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>
The above examples refer to BOS steelmaking, which is currently recognised as the route to optimum steel quality. However, similar developments will take place in arc furnace steelmaking. Indeed it is considered that in the future most if not all grades will be capable of production by this route.

Fig. 7 Tank degasser. Analysis capability: reduction with degasser 50%N, 40%O, 33%S and 38%C.
2.3 Casting

The initial implementation of continuous casting to replace the ingot route achieved major cost reductions. Most plants now effectively have 100% continuous casting and the major focus in recent times, and into the twenty-first century, is in improving the product quality and providing the capability to make new products whilst operating the equipment at minimal cost. As in steelmaking, this involves developments to improve the performance and capability of existing equipment and, where appropriate, targeted investment in enhancing existing casters or installing new ones to meet ever more demanding customer requirements. Caster enhancements are performed periodically, as seen in Fig. 8, which shows the recent history and potential future projects for the former British Steel plants of Corus.

Development of technologies which can be retrofitted onto existing casters offers a cost-effective means of enhancing product quality. Two examples under development in Corus are near liquidus casting (Fig. 9, Ref. 5) and vacuum tundish technology, both of which aim to improve significantly control of liquid steel delivery into the mould to enhance steel quality. Also, similar to steelmaking, improvements in computing power, software and sensors are leading to the development of on-line quality prediction systems to progress the development of ‘right every time’ operation. Overall it is clear that there is still scope for significant innovation in existing plant to improve profitability by making new and higher quality products to proactively satisfy the customer needs, whilst continuing to achieve reduction in costs.

3. NEW PROCESS TECHNOLOGIES

In addition to developments to existing steelmaking process routes, new process
technology has a key role to play in twenty-first century ironmaking and steelmaking. It has the aim to achieve:

- lower capital costs,
- to be economically viable at smaller scale (e.g. 1 Mtpa),
- lower operating costs,
- raw material flexibility and
- environmental benefits

by collapsing the process route. The main areas for new process technology are alternative ironmaking, EAF steelmaking and casting technologies.

3.1 Alternative Ironmaking

Alternative ironmaking is the conversion of Virgin raw iron bearing materials into metallic iron, by using any route other than the traditional blast furnace. It can be split into two distinct areas, direct reduction (scrap substitute) and smelting reduction (hot metal replacement).

3.1.1 Direct Reduction

Direct reduction processes product direct reduced iron (DRI). The chemical conversion from iron ore to DRI takes place in the solid phase and impurities in the feed iron ore are not separated in a slag as in a blast furnace, but remain in the product. Therefore, DR processes usually utilise a higher quality ore feedstock than the conventional blast furnace route. The product can be in some instances unstable, owing to its high surface area and tendency to reoxide rapidly causing combustion; therefore one method of reducing the risk of re-oxidation is to press it into
briquettes. The product is then known as Hot Briquetted Iron (HBI). HBI are small pillow-shaped blocks that have a high density sealed outer layer, which is non-absorbent and is therefore stable in air and water. This means HBI does not require special storage of shipping precautions. The disadvantage of HBI is that it usually has a lower carbon content than DRI and associated higher production costs, but is often favoured by merchant DRI/HBI sellers to reduce risks during transportation.

World DRI production has increased markedly in the last 6 years (Fig. 10), as the product is predominantly used in the EAF and therefore demand has increased with increasing global EAF steelmaking. DRI is approximately 94% Fe and is used as a high quality scrap replacement. This has the advantage of being able to produce high quality steel or it can be proportioned with a lower grade scrap material to maintain a particular quality level. In an age where scrap recycling is becoming more prevalent, a potential problem with residuals (or unwanted elements) from the recycled scrap can be avoided by dilution with the higher grade DRI. Current world DRI production stands at 37 Mtpa. The vast majority of this is gas based (Fig. 11) and therefore most plants are located near to large reserves of natural gas. However, in the long term, with decreasing gas reserves, one could envisage a growing role of coal based processes. These processes are limited at the moment owing to issues of quality and economies of scale.

3.1.1.1 Gas based direct reduction
Of all the DRI processes, Midrex is by far the most prevalent, accounting for approximately two-thirds of world production. Figure 12 shows a process schematic of the Midrex development. As stated earlier, raw material selection is crucial to DR process operation; as there is no melting phase within the process, there is no opportunity for residuals to be removed. Therefore, generally a higher quality of raw material is sought than that utilised for blast furnace operation and one can envisage at some stage in the future, with the forecasted growth in DRI
production, that obtaining the required grade material at an economic price may be problematic. The Midrex process consists of three main units, a reduction shaft, a reformer and a heat recuperator. In the reduction shaft, gases move counter current to the solids, which fall under gravity. The gases react with the solid to convert it from iron ore to iron without a change in phase. The reformer converts the waste gases from the reduction process back to hydrogen and carbon monoxide by reforming with natural gas. The recuperator utilises the energy associated with the waste gases from the reformer stage of the process, to preheat incoming cold streams, such as burner air and process gas, to maximise process efficiency.

Over the past twenty years or so the Midrex process has not changed funda-
mentally in process configuration; what has changed is the scale of the process units. In the mid 1970s a single unit may produce 400 ktpa of DRI, whereas a modern unit could produce up to 2 Mtpa. This gives obvious advantages in economies of scale. More recently 'reformer-less' DR processes are being constructed, with HYL operating such a unit. This saves on capital expenditure of the plant by using the hot DRI in the base of the reduction shaft as a gas reforming catalyst.

3.1.1.2 Coal based direct reduction
As stated earlier the majority of coal based processes have limitations on the quality of the DRI produced and also constraints on production capacity. The SL/RN rotary kiln (Fig. 13) method of DR production is the most widely used coal based process, but is limited to approximately 150 ktpa, thereby having a disadvantage in economies of scale compared with gas based processes. It consists of typically two rotary kilns, one for reduction and one for product cooling. Iron ore is blended with coal and fed to the reduction kiln, which is heated from within by burners. The reduced material is fed to the second rotary kiln for cooling before exiting the process as DRI. Typically the waste gas from such a process is used to heat a steam boiler or for direct power generation.

3.1.1.3 Fines based direct reduction
The processes mentioned above have limitations in that they need to utilise agglomerated ores as the feedstock. This has a cost disadvantage and therefore the next generation of DR processes will be fines based and as such can utilise a much cheaper and widely available raw material source. Being fines based, these processes will produce a briquetted product (HBI) as explained earlier. Examples of these processes such as Finmet and Circored, are being commissioned now and

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![Fig. 13 Schematic flowsheet of the SL/RN process.](image-url)
should provide lower operating costs. It is predicted that fines based hot briquetted iron (HBI) processes will account for the majority of reduced iron production during the next century, although at the moment they do not have the same economies of scale compared with agglomerated ore based DRI processes.

One of the above examples of a fines based process being commissioned at the moment is Circored (Fig. 14). Fines are pre-heated in a CFB (circulating fluidised bed). A series of cyclones and scrubbers clean the ‘off-gas’ which contains dust carryover from the CFB. The pre-heated fines then flow to the second reactor where the main reduction takes place. After leaving this unit, the pre-reduced fines then enter a final reduction stage. The solids are removed from this stage and heated so that they can be pressed into HBI. The gas from each unit is fed to the previous unit for process efficiency.

There are also coal based fines reduction processes being developed, such as Fastmet, Inmetco and Circofer. A main process configuration for these processes is based on the rotary hearth. Consider the operation of Fastmet as an example (Fig. 15). Iron ore fines, a binder and coal are mixed together and pelletised, they are then dried and fed to a rotary hearth furnace. Heated air and fuel are burnt in the furnace which causes the iron ore pellets to reduce to DRI. The hearth in this furnace is doughnut shaped and it rotates at about one revolution every ten minutes. The removal of the DRI pellets is a continuous process and they are removed by a screw conveyor. The product can be cooled in a rotary cooler as standard DRI or can be pressed into HBI if required.

Another form of DRI for consideration is iron carbide (Fig. 16). Iron ore fines are dried in a rotary drier and then screw fed into a fluidised bed reactor. Reduction gases, hydrogen and carbon monoxide, are generated by a steam reformer and are used to fluidise the bed and react with the ore. The reducing gases leave the top of the reactor and go through a cyclone, where the solids are recycled and the spent gases are scrubbed and fed back into the reactor or used in the burners. After reduc-
tion, the iron carbide leaves the reactor and is cooled through another screw conveyor.

Iron carbide is a different product to DRI as it is not iron but Fe$_3$C. This adds carbon value to the electric arc furnace and also reduces the reactivity of the product so that it does not require passivation. There have been two iron carbide plants built to date, neither of which are currently operating. The first was a single fluidised bed based unit built by Nucor, which ceased production earlier this year owing to a global dip in the demand for DRI derivatives by the merchant market and the fact that the plant had ongoing design problems. Nucor are currently seeking to sell the plant. The second unit, built by Qualitech, is a multiple fluidised bed
plant design but this ceased commissioning earlier this year owing to financial problems within the company.

To summarise, direct reduction processes can be considered to be both technically and economically proven, based on the agglomerated ore processes operating today. The majority of plants are gas based and of either Midrex or HYL design, but there is a move towards fines based processes for the reasons outlined earlier.

3.1.2 Smelting Reduction
Smelting reduction technologies produce a direct hot metal alternative to the blast furnace. Generally, composition and temperature are comparable and therefore these technologies can be integrated well into existing plants. While smelting reduction technology has been available for some time, only recently has it been seriously considered as a competitive alternative hot metal source. Global production of hot metal via these routes is still less than 2 Mtpa and therefore only accounts for 0.3% of world production. These processes are all coal based and do not require coke, hence claim to be cheaper and more environmentally friendly than the blast furnace based route. However, the only commercially proven process currently is Corex, developed by VAI. The Corex process flow sheet is shown in Fig. 17. Corex uses agglomerated ores as the feedstock and has a capacity for a C2000 unit of 750 ktpa based on pellet operation. A C3000 unit is proposed with a guaranteed production capacity of 1.08 Mtpa based on 100% pellet raw material. A limitation of this process, however, is the fact that it does require agglomerated ores such as pellets, sinter or lump ore.

3.1.2.1 Agglomerated ore based processes
Being the only commercially proven smelting reduction process to date, it is worth

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**Fig. 17** The Corex process.
considering operation of the Corex process. There are two main units, a melter gasifier and a reduction shaft. Coal and oxygen are injected into the melter gasifier (Fig. 17) via radial sidewall tuyeres; heat generated in this unit is used to melt the incoming DRI from the reduction unit. Off-gas from the melter gasifier is rich in reducing gases, carbon monoxide and hydrogen, which is used in the reduction shaft as the reductant. Ferrous feedstock into the shaft can be lump ore, pellets or sinter.

Spent gas from the reduction shaft is cleaned through a series of cyclones and the recovered ferrous dust is recycled into the bottom of the melter gasifier and the cleaned and cooled gas is routed to the reduction shaft. It is cooled because the off-gas from the melter is at 1100°C but needs to be about 800°C, to prevent melting and clustering within the reduction shaft. The melter is tapped periodically, producing blast furnace quality iron. A key parameter to the process economics is the value obtained from the large quantities of off-gas produced from this process. Power generation, oxygen production and DRI production are all options.

The Saldahna bay plant in South Africa is an example of a modern Corex based plant. A single C2000 unit provides approximately 650 ktpa of hot metal, which is utilised within a Conarc electric steelmaking facility. Along with the hot metal charge, scrap and DRI are proportioned to make up the feedstock balance, with the DRI being produced by a Midrex unit fuelled by the off-gas of the Corex unit. This configuration gives tremendous flexibility in raw material choice depending on current local economic conditions.

3.1.2.2 Fines based smelting reduction

A limitation with current generation of smelting reduction processes, as with DR processes, is the fact that they rely on agglomerated ores. The next generation will be fines based, but most of these are still several years away from being fully developed and include Hismelt, cyclone converter furnace (CCF) and direct iron, ore smelting (DIOS). Steel Dynamics, USA are developing a fines based process which is being commissioned at the moment and this will be discussed later in the next paragraph. The Corex process has operated successfully with a small percentage of fines in its feedstock, but a development of this to utilise 100% fines is called Finex. This differs from Corex in that the reduction shaft is replaced by a series of fluidised beds for pre-heating and pre-reduction, but the process is still several years away from being commercially available.

The Steel Dynamics process aims to directly reduce iron ore fines in a rotary hearth, which are then fed to a submerged arc furnace melter to produce a liquid metal for EAF refining. The rotary hearth is similar in design to the Inmetco process, which can be considered technically robust as can the intermediate smelting stage. Although these units have operated individually, it is thought that successful long term linked operation is still to be technically proven.

A European based process, developed by Hoogovens (now part of Corus), is the cyclone converter furnace, which converts iron ore fines into liquid iron. The ore fines and oxygen are injected into the CCF vessel so that the ore circulates around the top part (cyclone region), see Fig. 18. Granular coal and more oxygen are added
via a top lance. Coal burns with the oxygen, creating heat and reduction gases, hydrogen and carbon monoxide. The hot reducing gases mix with the iron ore fines and oxygen that are circulating in the top part of the vessel causing pre-reduction and post combustion, which melts the ore fines. The pre-reduced, molten iron ore fines collected on the water cooled wall of the vessel and flow, owing to gravity, into a pool of liquid iron. Final reduction occurs in the liquid pool and iron and slag are tapped periodically. The cyclone part of this process has been technically proven and it is proposed to utilise bath melting technology for process completion. The next stage is to build a semi industrial scale development unit of approximately 700 ktpa to fully test both units together; however there are no plans to build such a unit at the moment.

The direct iron ore smelting (DIOS) process, researched by a consortium of Japanese steelmakers also uses iron ore fines (Fig. 19). Waste gases from a smelting vessel are rich in reduction gases and are used to pre-reduce and pre-heat fines before they enter the smelting vessel. Gases that leave the smelting reduction furnace are cleaned and cooled in a cyclone and solids returned to the furnace. The smelting vessel melts the incoming pre-reduced material, again producing blast furnace type quality hot metal, which is periodically tapped. The 150 ktpa demonstration unit is considered to be technically proven, although none of the consortium members foresee an immediate need for the process within Japan. The process developers are currently seeking appropriate projects overseas for process commercialisation.

HiSmelt Corporation have been developing a fines based process at its Kwinnana research facility in Australia. The unit is 150 ktpa, with extensive research being carried out on raw materials, process optimisation, and engineering. The process is claimed to offer the option to operate on steel mill reverts in addition to iron ore, with the intention of significantly lower operating costs (process flow-
sheet, Fig. 20). Pre-reduced ore feedstock, vessel enlargement and increased oxygen usage are said to give a potential output from a single 8 m HiSmelt plant of 1.5 mtpa. The company are currently seeking steelmaking partners to join in the next stage of development, intended to be a 700 ktpa unit, although no firm project has yet been announced.

Fig. 19 The DIOS process.

Fig. 20 The HiSmelt process.
These future generation processes have the advantage of using cheaper raw materials, such as fine ore and coal but can also be flexible with material feedstocks. Several of the processes are claimed to be able to economically process reverts, such as recycled steel mill waste, and could therefore be a useful addition to an existing integrated works site.

In summary, smelting reduction technology will grow in particular areas of the world with cheap coal and growth potential. This may account for a significant proportion of new greenfield site capacity being installed. The Corex process is currently the only smelting reduction process to be fully commercialised. The amount of hot metal produced by smelting reduction processes worldwide is low by comparison to the blast furnace route. Fines based processes are still being developed, but will provide lower operating costs. Steel Dynamics are currently commissioning such a process. Other options such as Hismelt, DIOS and CCF are at key points in their development, and if investors are not forthcoming, further research will remain on hold. One attractive process option for these processes is that they can be used to recycle steel mill wastes and reverts. Smelting reduction technology developed originally as a proposed replacement for blast furnaces and coke ovens. However, the use is now being applied as a flexible hot metal source to electric arc furnace steelmaking, first examples of this being the SDI plant in Indiana, USA and the Saldahna Bay development in South Africa.

3.2 EAF Developments

Over the past thirty years, there has been remarkable progress in EAF development and particularly during the last ten years, plant manufacturers have designed, developed and supplied an increasingly varied and innovative array of new EAF technologies (Fig. 21). The operating performances of these latest technologies have underlined the considerable level of flexibility of the EAF process and the potential for further reductions in operating cost and productivity improvements. The vast majority of new steelmaking investment in recent years has been in EAFs. In Europe, liberalisation of the electric power market will help to promote and further enhance the competitiveness of EAF steelmaking, and several former European integrated steelmakers have already switched from BOF to EAF within their existing infrastructures, to replace end of life plant. In the USA the growth of the mini-mill is well known, whilst the majority of new investment in SE Asia has also been in arc furnaces. There is no doubt that the increasing trend to arc furnace production, relative to BOFs will continue.

Process flexibility is becoming increasingly important with the ability to operate on a variety of feedstocks economically being key to process selection (Fig. 22). The EAF is being developed to operate on a range of material feedstocks including scrap/DRI/hot metal, or a combination of any of these depending on local economies at the time. The increased use of hot metal in the EAF is a recent trend. This provides the benefit of increased productivity and virgin iron ore units for arc furnace products. This has led to furnace designs, which are effectively a hybrid
between the EAF and BOS in that they are equipped with both electrodes and a top oxygen lance. The twin vessel design supplied by Mannesmann is shown in Fig. 21 and the technology has been installed at Ispat, India and Saldahna Steel, South Africa. In principle this technology can operate with either 100% scrap or up to 70% hot metal.

Additionally, electric arc furnaces have comparatively low capital costs at say 1 Mtpa, when compared with conventional ironmaking. The viability at small scale and the ability to feed regional markets with products from greenfield site developments has led to this technology to be the first choice for new growth. Naturally, there is no single EAF design that will suit all requirements and any proposed EAF investment must consider a whole range of influencing factors. There are many EAF technologies achieving historically exceptional operating performances and many new alternative options, which are not yet fully proven. It is clear that future operational experience, particularly over the next few years, will help to separate
out ‘winners’ and ‘losers’. It is considered that future designs need to be highly flexible, have low capital cost and minimum operating cost, have low environmental impact and be highly energy efficient. This criteria would tend to direct future designs to a closed furnace, simple engineering, raw material flexibility depending on current economic considerations at the time, energy recovery (scrap pre-heating), with a high degree of automation and process control.

In summary, there has been remarkable progress in EAF development, with plant manufacturers designing, developing and supplying an increasingly varied and innovative array of new EAF technologies. The operating performances of these latest technologies have underlined the considerable level of flexibility of the EAF process and the potential for further reductions in operating cost and productivity improvements. Several former European integrated steelmakers have switched from BOF to EAF within their existing infrastructures; there is no doubt that the trend for an increasing EAF share of steel production relative to BOS will continue. With increased availability and use of virgin iron units in the charge and high usage of oxygen, many EAF steel producers are moving towards a hybrid technology that utilises the best of both the EAF and BOF and subsequently, are already matching the steel quality requirements that have been regarded, until very recently, as the domain of the integrated producers.

3.3 Casting Technology

Casting developments have aimed to reduce the number of process steps involved in producing the final product. Conventional slab casting and hot strip mill facilities may be up to 800 m in length containing reheating furnace, roughers and finishers. With the advent of thin slab casting the number of stages are reduced, typically reducing the length to 250 m. In addition to thin slab casters there have been and will continue to be developments in areas of direct strip casting and beam blank casting.

3.3.1 Thin Slab Casting

The continuous casting process, whereby liquid steel is converted into an intermediate solidified slab, bloom, or billet, is a developed technology in the steel industry. Thin slab casting processes are a development from the conventional slab casting process (>200 mm thick slabs) and reduce the costs from liquid steel to a finished strip gauge, by producing an intermediate gauge slab in the thickness range 40 to 90 mm. The thin slab caster is operated in line with an equalising furnace and a hot rolling mill, to convert the thin slab into a thin strip (0.8 to 12 mm thick) in one continuous processing step. The process is normally operated with arc furnace steelmaking, and is economically viable at about 1 Mtpa; however the process concept is now equally applicable to conventional integrated works. A layout for a thin slab casting plant is shown in Fig. 23.

Development of the thin slab casting process concept has been ongoing for a number of years with competing technology, such as belt casting (Hazelett type
process), casting between two large diameter rolls (SMI) and experimentation with modified slab casting moulds (SMS, MDH, Danieli, VAI, SMI). Most of the development work with the new techniques has been terminated for slab production. Process concepts based on modifications to existing slab casting technology have flourished and all the commercial thin slab casting plants in existence use this type of technology.

Early development work for the thin slab casting concept, designated the compact strip production (CSP) process, was carried out in Kreutzal, Germany, and the first commercial application of the concept for Nucor at a new greenfield site in Crawfordsville, Indiana, was commissioned in 1989. This mill originally had five rolling stands but a sixth was added subsequently to enable thinner gauge materials to be produced. Today plants are built with either six or seven stands to enable strip at a thickness of <1 mm to be produced in a number of continuous processing steps. For example, a CSP thin slab casting and rolling plant has been supplied by SMS for Thyssen Krupp Stahl, with a capacity of 1.8 Mtpa at the Bruckhausen Works, Germany.

Other developers offer similar thin slab casting processes, such as MDH (now taken over by SMS) which is building a plant at Ijmuiden, Holland, for the Corus group and is being commissioned during January 2000. This plant is capable of producing 70 mm thick slabs, without further in-line rolling. The first SMI thin slab casting pilot plant was built at Sumitomo Metals' Kashima Works in the early 1990s and the first commercial plants using the technology were built in the USA at Decatur, Alabama (Corus, LTV and SMI consortium) and Delta, Ohio (North Star Steel/BHP consortium).

As flat product mini-mills improve the quality of the liquid steel supply and the control of thin slab casting operations, an increasingly wider range of products are possible. For example the Danieli built caster at Algoma Steel is claimed to be able to produce peritectic grade steels, and a number of plants claim to be able to produce auto grades for non-exposed body parts. The low cost base of these plants and improving quality brings them increasingly into competition with the integrated steel plants.
Many of the flat product mini-mill producers including Nucor (Hickman), and Steel Dynamics (SDI), USA are adding value to the product by installing their own cold rolling mill and galvanising facilities. SDI has been producing strip for non-exposed parts in the automotive industry for some time and is confident that in the future, it will be able to make strip for exposed applications as well.

Thin slab casting for stainless grades has been slow to develop. The CSP mould at ASTerni has been used to cast both ferritic and austenitic grades, although the most success has been claimed for the former. AST are well advanced in installing the CSP caster in line with a tunnel re-heat furnace and the roughing mill. Armco have installed a medium thickness of approximately 700 ktpa capacity at its Ohio plant with most of the production being ferritic stainless grades, particularly type 409. Whilst Nucor has been producing trial casts for many years, they have still not achieved their production targets for these grades.

In summary, thin slab casting is now a proven technology and the majority of new flat product casting plants use thin or medium thickness slab casters. The technology has the advantage over conventional slab casters of being economically viable at capacities as low as 1 Mtpa and provides a good fit to both mini-mill and integrated works based plants.

3.3.2 Direct Strip Casting
The direct strip casting process is used to convert liquid steel into a hot band equivalent thin strip product in one process step. There are a number of different process concepts under investigation including single roll casting, belt casting and twin unequal roll casting but the most common process being the equal twin roll strip caster (Fig. 24). A key part to these processes is the control of steel distribution and flow rate into the roll entry of the casting machine. Both steel and copper alloys have been used in the roll manufacture, although from a heat removal perspective copper alloys are preferred, usually in the form of a water cooled sleeve on a steel arbour. A thin surface coating of nickel protects the copper alloy from wear and erosion from the high liquid metal temperatures. The limits on cast thickness for twin roll casting machines are expected to vary between about 0.5 and 5 mm, which enables casting speeds as high as 150 m min\(^{-1}\) to be achieved at the thinner gauges.

The first commercial application for the concept was at Nippon Steel Corporation’s Hikari Works, Japan for the production of stainless steel strip (1330 mm wide (max) \(\times\) 2.5 mm thick with a design capacity of up to 500 ktpa), although this plant is still in the commissioning stage some eighteen months after start-up. Other developments have been that Krupp Thyssen Stainless have placed a contract with VAI to build a thin strip caster plant at its Krefeld Works, Germany (1350 mm wide (max) \(\times\) (1.5-4.5) mm thick with a design capacity of 400 ktpa). Usinor of France have recently joined this project which has been renamed Eurostrip.

Direct casting studies for the production of thin strip in carbon steel grades has not received the same high level of funding as that for stainless steel, although the technical success at BHP indicates that a commercial plant for the production of carbon steel grades could become a reality in the near future and BHP are seeking
partners for the first plant. Typical throughputs for a commercial strip casting plant would be 300 to 500 ktpa.

In summary, direct strip casting, particularly 304 grade stainless steel strip, has received significant research expenditure since the beginning of the 1980s. The incentive for stainless steel producers was the lack of hot rolling facilities on many producer sites, which forced hire rolling of slabs to hot band gauges, often involving significant transport costs between sites. During the past twenty years several of the strip casting development projects have been terminated, and some producers have chosen to install Steckel mills to overcome the shortfall in hot rolling capacity. NSC Hikari Works, however, installed the first production direct strip caster and commissioning is now underway. Krupp Thyssen Stainless, have recently placed a contract with VAI to build a thin strip caster plant at its Krefeld Works, Germany, (Eurostrip). BHP are confident of their direct strip casting process for carbon steels and are seeking partners for a commercial unit.

### 3.3.3 Beam Blank Casting

The beam blank casting process converts liquid steel into a dog-bone shape, thus eliminating some of the roughing requirements normally involved in rolling a cast bloom into a beam or similar section. The process was first developed at BISRA, Sheffield in the 1960s with the first commercial application of the process concept at Algoma Steel, Canada in 1968. Subsequently, the technology was slow to take off, with two beam blank casting moulds installed on one strand of existing bloom casters in Japan in the 1970s, and one installed in the United States. This set the pattern for the future growth of the technology, with beam blank moulds replacing one bloom mould in a bloom casting plant.

Today there are more than thirty plants casting on one or more beam blank casting moulds. These are primarily in the Far East and the USA, although Arbed is a major supporter of beam blank casting technology in Europe. Typical beam blanks
are in the form of a ‘knifed’ bloom in which the web thickness is more than 100 mm, although some developers produce near net shape beam blanks in which the web thickness can be as little as 50 mm.

Many of the developments are coupled with conventional bloom or billet casting machines, and some machines operate simultaneously with bloom and beam blank moulds. There is some flexibility in operating capacity with commercially viable operations with capacities of only 500 ktpa. Beam blank semis can be used to produce an increasingly large number of finished product sizes, and the Thueringen plant at Unterwellenborn produces 220 different sections from just three different beam blank sizes.

In summary, it is likely that many of the new long product mini-mills for section production will include the option of a beam blank casting mould.

4. ENVIRONMENTAL SUSTAINABILITY

In the future there will be an increasing emphasis on environmental sustainability, the definition of which has generally been agreed as being ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’. This points to greater levels of recycling and steel products and processes with lower environment impact, including CO₂ emissions. The steel industry is well placed to respond to these challenges to ensure that it retains its position as the material of choice. Examples of ongoing developments, the impact of new process technology and some longer-term perspectives are given below.

4.1 Ongoing Developments

4.1.1 Lightweighting of Products

Around 25% of steel production in Western Europe, Japan and North America is used in the automotive market. Under the auspices of the IISI Porsche Engineering were commissioned to design an ultra light steel auto body (ULSAB). This $22M study, funded by a consortium of thirty-five steel companies, demonstrated the feasibility of producing a body with a weight saving of 25% with improved torsional and bending stiffness but without increased costs. This development incorporates high strength steel, laser welded blanks and hydro forming and these technologies are now being adopted in new car models. The environmental benefit is two-fold both in terms of reduced weight per car and also improved fuel consumption over the car’s life. Further work is now ongoing with the IISI to achieve weight reduction in closures (doors, bonnet, etc.) and suspensions. Another example is lightweighting of steel beverage cans where the weight of a 33 cL can has reduced from around 36 to 20 g over the last twenty-five years and further reductions are under development.
4.1.2 Energy Reductions
The steel industry has made considerable reductions over the years. For example, the UK plants of Corus now produce 25% less CO$_2$ in total than in 1980 while making the same tonnage of steel. The future lies in improving the operating efficiency in all processes by making many small improvements in energy consumption.

4.1.3 Increased Recycling
An option to reduce the amount of CO$_2$ produced per ton of steel is to use as much scrap as possible in the steelmaking process. The environmental burden of making steel has already been paid on this scrap so that using it in electric arc furnaces more than halves the amount of CO$_2$ produced, depending on the source of the electricity (hydropower, nuclear power, gas or coal-fired power). In addition techniques have been developed that enable the BOF to be fed with 40% or more scrap which may reduce the CO$_2$ generated per tonne of steel by 15%. However, extra scrap can reduce productivity and scrap prices vary considerably, such that it is not necessarily economically viable to deploy this technology in all circumstances.

Steel is already the most recycled material in the world and 320 million tonnes are recycled out of a production of around 750 million tonnes. There is potentially scope to increase this in the future.

4.2 New Process Technology
The new processes described in Section 3 in general offer improved environmental performances compared with the current generation of technology. For example, smelting reduction using coal directly and thus avoiding cokemaking leads to significant reduction in particulates, NO$_x$, SO$_x$ and potentially CO$_2$ emissions. The growth in gaseous direct reduction also results in lower CO$_2$ emissions. The increased use of arc furnaces projected in the future also provides benefits when associated with increased levels of scrap recycling. The developments in casting provide energy savings by avoiding the need for re-heating.

Thus, the new generation of primary process technology currently emerging which will find increasing application in the coming years offers further benefits to reduce the environmental impact of steelmaking and improve sustainability. However, as noted earlier, these technologies usually only become economically viable to replace end of life plant or when considering new developments.

4.3 Longer-term Developments
The drive of sustainability is prompting world-wide development of energy sources or technologies which aim to reduce CO$_2$ emissions. Renewable sources, such as solar, wind, wave and biomass, are being developed. Nuclear energy offers CO$_2$-free electricity but there are currently public pressures against further expansion. The possibility of a hydrogen based economy is also being promoted. For
fossil fuel fired power plants the possibility of CO₂ sequestration is being examined. The development of these energy sources and technologies is essentially the remit of energy companies, supported where appropriate by government funding. However, they can be effectively applied in steelmaking. Many of the technologies produce electricity which, together with the projected growth in EAF steelmaking, will further reduce CO₂ emissions. For ore based reduction, there has been a history of innovation and the possibility of employing electricity, biomass or CO₂ sequestration, to supplement existing technology or form the basis of new technologies are potential challenges and opportunities for the future.

5. CHOICE OF PROCESS ROUTE

When investing in plant in growth areas, there are many different process combinations available and these must be tailored to meet local needs with respect to:

- market demand,
- product mix and quality,
- feedstock and energy, and
- local infrastructure.

Options available include the BF/BOS route for high growth areas, where demand for a production capacity of say, 3–4 Mtpa is required. However, this is a highly capital intensive development which requires a wide market for product sales. A schematic of the comparative process inflexibility is shown in Fig. 25. The high growth rate forecast for the Asian region, before the recent crisis, warranted potential investment in BF/BOS equipment, but investors are now a little more cautious and new investment in that region is expected to be mainly EAF/smelting reduction technology.

EAF developments are appropriate for smaller regional markets with good scrap and electricity availability. This is a lower capital intensive route than a traditional integrated works and has the added flexibility of operating on a range of feedstocks, such as scrap, DRI/HBI, pig iron and hot metal.

Smelting reduction processes are appropriate for areas with cheap coal supply feeding a similar size market to the EAF choice. Modern plants, such as the Saldalana Bay development in South Africa use a combination of the above, with hot metal being produced from a Corex unit, the off-gas of which is used to produce DRI. These materials are then fed to an EAF that can utilise any combination of the above plus scrap. This results in a highly flexible production unit, that can tailor material requirements depending on current economic conditions. When replacing end of life plant, the options are similar to the above plus rebuilding existing assets. A summary of process route options is given in Table 2.
6. SUMMARY

In summary, for the near term, the strategy in areas where there is little or no growth is to maximise the profitability and competitiveness of existing plants, prior to replacing them at the end of their life in a cost effective way. In areas where there are growth opportunities there is a wide range of process technologies available, which can be tailored to match local market demand, feedstock and energy availability.

Sustainability will be of increasing importance in the twenty-first century. Steel is well placed to meet this requirement. It is already the most recycled material in the world and further increases are possible. Steel products will be further designed with re-use or recyclability in mind and more of the existing steel in the marketplace will be recycled in future, thereby reducing the need for virgin steel requirements. It is essential that the steel industry continues to develop to remain

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**Table 2** Summary of process routes.

<table>
<thead>
<tr>
<th>Route</th>
<th>Capital cost</th>
<th>Status</th>
<th>Scale of operation, mtpa</th>
<th>Potential for application</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF/BOS</td>
<td>$400/at</td>
<td>Proven</td>
<td>4–6</td>
<td>High growth area, e.g. China, Taiwan</td>
</tr>
<tr>
<td>EAF</td>
<td>$100/at</td>
<td>Proven/development</td>
<td>1–2</td>
<td>Favoured route where electricity and scrap available</td>
</tr>
<tr>
<td>DR gas</td>
<td>$140–200/at</td>
<td>Proven/development</td>
<td>1.3</td>
<td>Requires low cost NG</td>
</tr>
<tr>
<td>DR coal</td>
<td>$140–170/at</td>
<td>Proven/development</td>
<td>0.25</td>
<td>Limited</td>
</tr>
<tr>
<td>SR</td>
<td>$300/at</td>
<td>First plants/development</td>
<td>0.8</td>
<td>Low cost coal</td>
</tr>
</tbody>
</table>
the material of choice into and through the next millennium. This is in the face of fierce competition from competitive materials such as aluminium, plastics, composites and concrete for construction. The steel industry must work ever closer with its customers to add value to their products and assist in product design for the future benefit of steel and the material life cycle.

In the past, the steel industry has not undergone the same degree of globalisation with acquisitions and mergers as other industries. However, this process has become evident over the last decade and is predicted to continue in the twenty-first century. An example is the creation of the Corus Group, emanating from the British Steel and Hoogovens merger, which demonstrates the realisation that to be a key business within the steel industry, a truly international presence needs to be achieved. For material industries to remain competitive throughout the twenty-first century they need to either become excellent and regional or global suppliers, or to forward integrate into customer components and systems. The steel industry will succeed in meeting the challenges and opportunities presented now and throughout the twenty-first century and will remain the material of choice for customers.

7. REFERENCES

Appendix: Brief Histories of Some British Iron and Steel Companies

BROWN BAYLEY STEELS LTD

by C. Bodsworth

This company was founded in Sheffield, in 1871 under the name of Brown, Bayley and Dixon. Two years later it became a limited liability company. George Brown, one of the founding directors, was a nephew of John Brown who had resigned in the previous year from the company that he had created, and helped to set up the new company as a competitor. A chronological account of the developments during the first century of operation has been published.

George Brown had been employed at the Atlas works of John Brown before he formed a partnership to establish the new works on a greenfield site between Sheffield and Rotherham. Most of the other works, such as Cammell's and John Brown's, which had been established in this area during the previous three decades, had started life as manufacturers of wrought iron and had progressed to steel production via the cementation and crucible processes before the advent of the Bessemer converter. The new works was designed specifically to exploit the acid Bessemer process, with four 6 t converters to produce up to 60,000 t of steel per annum, but puddling furnaces and six cementation furnaces were added in 1874 to produce special grades for forgings. A laboratory was provided for chemical analysis of the melts. The chemist was Dr J. O. Arnold who, in 1899, became the first holder of the chair of metallurgy at Sheffield University.

The iron- and steelworks that started at this time were built mainly in response to the internal and export demand that had arisen from the railway mania which was spreading from Britain to Europe and the Americas. Brown, Bayley and Dixon complied with this scenario and the initial processing plant comprised rail, spring, tyre and axle shops which, together with the forge, produced mainly railway products. The timing was unfortunate, however, for within 2 years of the opening of the works the rate of railway development declined rapidly. There was a severe recession through the industry from 1873 to 1876 and the company failed to return a profit. The culminated in a voluntary liquidation and the firm was relaunched as Brown, Bayley, Dixon and Co. Ltd. In the following year the name was changed again to Brown Bayley's Steel Works Ltd.

There is evidence that the company was one of the first in Britain to apply successfully the basic Bessemer (Thomas) process for steelmaking. Problems were being experienced in lining the converter with lime-magnesia blocks. A patent was
granted to the company in 1878 for bonding the blocks together with hot oil, which gave satisfactory performance until the tar bonding technique was perfected. Difficulties were also being experienced with phosphorus reversion from slag to metal during holding following the afterblow. Brown Bayley developed the technique of removing the slag at this stage, adding more lime and giving another short afterblow. This procedure rapidly became the standard practice for all operators of the basis converter process. The first successful cast was made towards the end of 1879 and 400 t of basic Bessemer steel was produced in the works during the following year. The manager of the melting shop, Arthur Cooper, left to join the newly formed North Eastern Steel Co. at Middlesbrough where the first heat of Thomas steel was produced successfully in 1883.

The steelmaking capacity was increased in 1888 by the installation of an open hearth furnace and crucible furnaces. Two years later another two open hearths had been added to replace the puddling furnaces. The manufacture of rails was discontinued to allow increased production of billets and bars, but wheels, tyres, springs and axles remained as major products. By the end of the century, the company had a nominal capital value of £150,000.

In the first decade of the twentieth century the area of the works was increased to accommodate two more open hearth furnaces and a press shop housing a 1200 t press for tyre production. A metallurgical laboratory was opened under the direction of Mr J. H. G. Moneypenny. He is remembered as the author of the book 'Stainless iron and steel', which became the standard reference work on this topic.²

The company’s interest in alloy and stainless steels developed following the appointment of Mr Harry Brearley as the works manager and then as the technical director in 1915. Brearley had pioneered the development of ferritic chromium steels while employed by Thomas Firth and Co. Ltd, but resigned from that company after a prolonged dispute over patent rights.³ Brown Bayley’s now installed a 7 t electric arc furnace and began the large scale production (for those days) of alloy steels. During the latter part of the First World War it became the major producer of Ni-Cr alloy steel blooms for forging into crankshafts for airplane engines. The Bessemer converters were demolished at the end of the war to make more room available for electric melting.

The production of stainless steel was primarily a postwar development. A low carbon (0.07%C, 12%Cr) stainless steel was marketed by the company in 1920. A licence for the manufacture of austenitic stainless was obtained from Germany in 1924 and 3 years later the first Ni-Cr-Mo steel was sold as Brown Bayley’s BB4K steel, together with a 15%Cr, 10%Ni ‘Anka’ steel. Attempts to produce a corrosion resistant steel that could be hardened and tempered resulted in the production of a low carbon, 20%Cr, 2%Ni composition, which was marketed as ‘Two score’ (British standard S80). Stainless steel chains made from this material were supplied to reinforce the domes of St Paul’s Cathedral in London (1930 and 1931) and the Church of the Holy Sepulchre in Jerusalem (1933). A subsidiary company was opened in South Africa in 1931 to supply steel for the gold and diamond mines.

As the orderbook began to recover from the recession of the 1920s the adjacent
site of the Yorkshire Iron Works was acquired to allow room for further expansion. An 8 t electric arc furnace was built in 1934 and two 20 t furnaces were added in 1938–1939. Stainless steel sheet and strip mills were built and the forge was expanded with the installation of horizontal upset forging machines.

The plant was fully engaged in the production of materials for armaments throughout the Second World War. In 1940, a landmine demolished the buildings housing the rolling mills. Steel production was not disrupted, but the ingots had to be transported to other works for rolling until the buildings had been re-erected.

The British steel industry was nationalised in 1951 and the firm was taken into state ownership. In anticipation of this event a new company, Brown Bayley Steels Ltd, was formed to operate the parts of the operation that would be taken into state ownership while the parent company retained control of the subsidiary firms of Hoffman Manufacturing Co. Ltd, Farnley Iron Works Ltd, The Stainless Steel Sink Co. Ltd and Taylor Rustless Fittings Co. Ltd. At that time, the works contained two acid and two basic open hearth furnaces of 45–50 t capacity and three electric arc furnaces of 10, 20 and 25 t capacity, feeding a cogging mill, hot and cold sheet and strip rolling mills, bar and tyre mills.

When the industry was denationalised in 1955, Brown Bayley Steels was converted into a public company with Brown Bayley Steel Works Ltd owning half the shares. During the period under state control, a 1 t and a 5 t induction furnace had been commissioned, while the three oldest open hearth furnaces had been demolished and spring manufacture had been discontinued. Two 40 t open hearth furnaces were now built and a 250 kg induction furnace was installed in the stainless steel foundry.

A new forging and press shop was constructed in 1960, equipped with 1000 and 1500 t presses and ring rolling machines. A vacuum casting plant and a 700 kg capacity electroslag refining unit were installed in 1967. A new 800 mm blooming mill was built to supply the 700 mm billet mill.

When the industry was renationalised in 1967 the annual production of the works was well below the criterion set for acquisition by the Government, but, in 1969, the Industrial Reorganisation Corp. made a compulsory purchase of all the shares in the holding company and its subsidiaries, although the company continued to trade under its own name. The Hoffman Manufacturing Co. was re-sold to form part of the Ransom, Hoffman, Pollard Ball Bearing Co. At that time the company was producing 125,000 t of molten steel per annum. Two years later a 1000 t combined forge–hammer press was installed and a vacuum oxygen degassing plant for stainless steel production replaced the 10 t arc furnace. The Rotherham Tinsley rolling mills were also bought out.

Faced with strong competition from imports and a strict pricing regime imposed by British Steel Corp. (BSC), the prosperity of the independent steel producers declined rapidly over the next few years, and the company was taken over by Dunford-Hadfields Ltd in 1973. Two years later a 100 t arc furnace was commissioned and the last of the open hearth furnaces was demolished in an effort to improve profitability. Dunford-Hadfields was in turn taken over by the Lonrho
group in 1977. The continued decline in orders, however, resulted in financial losses which were exacerbated by a national strike of steelmakers. This resulted in the formation of Hadfields Holdings Ltd in 1981, a company jointly owned by Lonrho, GKN and BSC. The Brown Bayley works was closed down immediately. The buildings were demolished and the site is now occupied by a sports stadium which was built for the International Youth Games.

**COLVILLES LTD**

**BY I. M. MACKENZIE**

**Birth and Growth**

In 1861 David Colville, in partnership with Thomas Gray, opened a works in Coatbridge to manufacture malleable iron. This was a period of rapid expansion of the Scottish ironmaking industry and the venture flourished with an output of about 600 tons/month.

In 1870, however, the partnership broke up and David Colville, assisted by his two sons John and Archibald, decided to set up his own company and looked for a suitable location. They were offered a promising site in Motherwell and in 1872 the Dalzell works of David Colville and Sons commenced production of malleable iron. At about the same time the Steel Co. of Scotland came into existence to manufacture steel at Hallside works in Newton, using the recently developed Siemens open hearth process.

As the end of the decade approached, it became evident that malleable iron had no future and David Colville sent his youngest son, also David, to work at Hallside to gain experience of open hearth steelmaking. In 1880 the Dalzell works switched to steelmaking, with five open hearth furnaces each of 10 tons capacity. Ingots were processed into plates for the shipbuilding industry, which was ending its short flirtation with wrought iron in favour of steel. By 1885 the shipbuilding industry on the Clyde was booming and there were ten firms in Scotland operating seventy-three open hearth furnaces using purchased pig iron. It is an interesting feature of the Scottish industry that none of the iron producers moved into steel production. One reason undoubtedly was that the high phosphorus iron produced from the local black band ironstone was unsuitable for use in the Bessemer process. Although expensive trials were carried out, only the Glengarnock Iron and Steel Co. installed basic Bessemer converters, and in 1885 it also began a change to the open hearth process.

* Most of the factual information has been derived from the book ‘Colvilles and the Scottish steel industry’, by Peter L. Payne (1979). See also ‘A technical survey of the Colville group of companies’, *Iron Coal Trades Rev.*, 1956.
David Colville and Sons, which had in 1896 become a private limited liability company, invested its profits in the continuous improvement of the production facilities at Dalzell works. In 1895, two more open hearth furnaces of 25 ton capacity had been installed and a further three of 40 ton capacity were added three years later. By 1900, the works had twenty furnaces, five of 50 ton capacity, and by 1910 several 100 ton furnaces were in operation. Comparable improvements were made in the casting and rolling departments. In 1913 the works had a 36 in by 10 ft reversing slabbing mill capable of rolling ingots up to 50 tons in weight.

Thus, it was during the period from 1885 to 1914 that David Colville and Sons established its position of supremacy in the Scottish steel industry. The company's growth is compared with that of its local competitors in Fig. 1. Apart from local competition, the company faced stiff competition from English companies, such as Consett, and was by far the most successful Scottish firm in meeting this challenge. By 1914 Dalzell was one of the largest steelworks in Britain.

To what did Colvilles owe its success? It has been suggested that the other companies were run by businessmen with an interest in steel whereas David Colville and Sons were run by steelmen with good heads for business. David Colville placed great importance on maintaining the loyalty of employees whose services he particularly valued, and shares in the company were offered to such individuals. Among those included in this scheme was John Craig who, as a teenager, had been recruited by Dalzell works as an office boy.

There were other successful Scottish steel companies but they tended to concentrate on special products. Beardmores specialised in the production of forgings and

![Fig. 1 Colvilles' steel production (1890–1920) relative to that of local competitors.](image-url)
armour plate. Stewarts and Lloyds, formed in 1903, concentrated on tube and pipe production.

**War and Takeovers**

While David Colville and Sons was the largest Scottish steel producer and was profiting from the policy of making continuous technical improvements, the firm was a one product company (steel plates for shipbuilding) that had not got involved in either forward or backward integration, with no ironmaking or involvement in end product manufacture.

The outbreak of war placed great pressure on the steel firms to increase output and not all were able to respond to the challenge. In 1916, at the instigation of the Ministry of Munitions and with financial assistance from the Government, David Colville and Sons took over two other steelmaking companies, the Clydebridge Steel Co. and the Glengarnock Iron and Steel Co., both of which had been underperforming. Like the Dalzell works, the Clydebridge steelworks produced plates and was well equipped. Glengarnock works had blast furnaces, open hearth furnaces, and Bessemer converters and produced heavy sections and rails.

Now that its plant included blast furnaces as well as gas producers it was essential that Colvilles took steps to ensure supplies of coal. The Ministry of Munitions was against opening up new coalfields while there was a war on, so Colvilles acquired the established colliery firm of Archibald Russell Ltd. To assure a supply of ingot moulds Colvilles also participated in the establishment of Fullwood Foundry Co. Ltd.

Colvilles was successful in substantially increasing the output of all the works and over the period 1914–1920 annual ingot output increased from 310,000 to 829,500 tons. Perhaps more significantly the company's share of the total Scottish output had increased from 24 to 46%. The workforce had grown from 2800 to 18,000. However, for the first time in its existence, the company had very large debts.

During the war, there had been a most significant change in control of the company. Both David and Archibald Colville, who had taken over the running of the firm from its founder, died. There was no other member of the family qualified or available to take over the chairmanship and difficult times were in prospect. John Craig became Chairman and Managing Director. The wartime priority had been for more steel at all costs, with no consideration given as to how the industry would make the transition to peacetime. With hindsight it is easy to identify the serious errors of judgement made, not just by Colvilles but by the Scottish steelmaking and shipbuilding industries in general, in the years following the war. It appears that everyone anticipated a continuing boom.

The Colvilles board was concerned about the limited range of outlets for the company's increased steel output. It was decided there was a need to diversify and also to take steps to safeguard supplies of vital raw materials. To assure continuation of its market for sheet bar, Colvilles bought the Smith and McLean Co., which
produced galvanised sheet, and also the Inshaw works of Cox and Danks, which had ceased production with a stock of 20,000 tons of steel billets that Colvilles could use. At this juncture the board received an approach from two young metallurgists, Dr Andrew McCance and T. M Service, who had been working for Beardmores. They saw an opportunity for producing magnet and other alloy steels in Scotland, and asked if Colvilles would back them. Colvilles' board responded to this request by creating the Clyde Alloy Steel Co. using the Inshaw works.

In 1919, Colvilles decided that it would be advantageous to run a scrapyard and, after various negotiations, the Motherwell Machinery and Scrap Co. came into being. To assure supplies of limestone, Colvilles bought the Carlough Lime Co. Fullwood Foundry Co. bought the Hamilton foundry of John Frew and Co. Ltd, which produced a wide range of iron castings for steelworks.

In the immediate post-war period, the ship building companies feared that their activities might be hampered by shortage of steel and therefore bought up virtually the entire Scottish steel industry. Harland and Wolff established a relationship with David Colville and Sons and in 1920 bought 95% of the company's shares. However, they left the running of the company to John Craig and his board, with minimum interference.

Rationalisation: Thirteen Years of Frustration

By 1921, the post-war boom had collapsed. The Association of Scottish Steelmakers, which had been fixing prices, ceased to do so and prices fell below production costs. While this hit David Colville and Sons hard, it had an even greater effect on less efficient companies, such as the Steel Co. of Scotland and the Lanarkshire Steel Co. It was recognised that there was a need for radical restructuring of the whole UK steel industry and, with the Government egging them on, the Scottish companies were involved in repeated and protracted negotiations about the possibilities of amalgamations. Over a period of no less than 13 years various proposals reached an advanced stage of negotiation, but in every case there was failure to reach agreement.

However, in 1931 one set of negotiations reached a successful conclusion. There was still a problem of a shortage of ironmaking capacity in Scotland and John Craig held meetings with Peter Baxter, Managing Director of James Dunlop and Co. (the proprietors of Clyde Iron Works), with a view to establishing a closer relationship between the companies. The outcome of this initiative was that a new company was formed, Colvilles Ltd. The new company acquired the Dalzell, Clydebridge and Glengarnock works from David Colville and Sons and the Clyde Iron Works from James Dunlop and Co. David Colville and Sons continued to operate the other subsidiaries.

There were also minor rationalisation agreements. Beardmores, which was in serious financial difficulties, transferred all its Mossend Works business in plates and sections to Colvilles and in 1934 Colvilles purchased the works. In 1933, an agreement was reached whereby Colvilles took over the plate business of Stewarts
and Lloyds, undertaking to supply plates and tube billets to the latter’s Clydesdale works.

During this period, despite substantial debts and difficult trading conditions, Colvilles managed to continue to improve its plant. The management was very resourceful and several important plant acquisitions were achieved very much on the cheap. In several cases, virtually scrap prices were paid for items of plant being sold off by companies that were giving up the struggle against adversity. The plant was renovated by Colvilles engineers and installed in works where it was needed. There were technical developments at Clyde Alloy, where stainless steel was produced by the open hearth process, the only company in the world able to do this.

In 1936 the logjam of reorganisation was broken. Colvilles Ltd converted to a public company. Released from the financial restraints that had hobbled it for a decade and a half, the public company proceeded to buy all the shares of the subsidiary companies of David Colville and Sons. Then it managed to buy the Steel Co. of Scotland and the Lanarkshire Steel Co. These transactions completed the process of amalgamation, which the government and the Iron and Steel Federation had been urging for so many years (Fig. 2).

Fortuitously, at this time demand for steel showed a marked increase, mainly due to a boom in the house building market and to the start of rearmament. Ingot output, which had slumped to only 275,500 tons in 1932, was back to the 1920 level of over 800,000 tons, over half the total Scottish output. This led to a shortage of cokemaking, ironmaking and steelmaking capacity. However, it was the remaining small independent companies that suffered worst from these shortages.

Colvilles went ahead with plans for the expansion of ironmaking at Clyde Iron Works and constructed a bridge across the River Clyde so that molten pig iron could be transported to the Clydebridge works, which converted to the hot metal
open hearth process. The Government encouraged Colvilles to start to produce armour plate at the Mossend works, which Colvilles had bought from Beardmores.

So, by 1940 Colvilles Ltd had become the overwhelmingly dominant Scottish steel producer and its chairman, John Craig, had established its organisational structure. There was a main board of directors and several functional organisations serving the whole group, including a Head Office which dealt with purchases and sales, electrical and mechanical engineering departments and an embryonic metallurgical research department. Individual works had their own boards of directors, with John Craig as Chairman of all but one of them. The works all had their own testhouses, chemical laboratories and metallurgical departments.

While the desired amalgamation had at last been brought about, there was no opportunity to carry out the needed restructuring of the production facilities because of the demands of wartime. Colvilles had plenty of immediate problems to solve. The principal technical problem was operating the blast furnaces on home ores, but the works had also to master the production of many new types of steel such as tank armour, non-magnetic steel and bulletproof plating. The solution to these and many other problems was facilitated by the creation of an Executive Board, comprising works managers and the heads of the group functional departments. In the course of the war the group achieved a total output of 9 million tons of steel.

Another Seven Years of Gridlock

Towards the end of the war Colvilles got back to making long term plans. The group had to deal with the major problem of a shortage of ironmaking capacity but was also very aware that there could be problems with the market. The principal purchaser of Scottish steel had always been the shipbuilding industry and shipbuilding was showing signs of returning to bad times. Colvilles wished to minimise any risk and therefore did not want to expand productive capacity too much, and needed to develop products to suit a changing market situation.

However, steel companies were not free to act as they wished. The Government had not relinquished the control of the industry assumed during the war, and all company plans had to be approved by the Government Control Board. The development plan that Colvilles submitted for approval in 1944 was very conservative and involved little more than the closure of some obsolete small mills, expansion of production at Clyde Iron, Dalzell, Clydebridge and Lanarkshire works, and the construction of an iron ore handling plant on the River Clyde in Glasgow. However, the Government and the British Iron and Steel Federation (BISF) favoured a much more ambitious plan requiring Colvilles to give consideration to the construction of an entirely new works on a coastal site. This would have involved the closure of existing works, with very serious consequences for the communities dependent on them. Colvilles strongly opposed the BISF plan and a deadlock ensued. A compromise plan put forward by the BISF in 1948 was not acceptable to the Iron and Steel Board.
While Colvilles was able to proceed with a number of comparatively modest plant development projects, including the reconstruction of one of the melting shops at the Dalzell works, no progress could be made towards meeting the two priority requirements of increasing pig iron production and improving facilities for unloading iron ore. It was not until 1954 that approval was given for plans to build an ore terminal at General Terminus Quay and a new ironmaking and steelmaking plant on a site in Motherwell adjoining the Dalzell and Lanarkshire works. Three years later the plant at Ravenscraig works was in operation with two blast furnaces and a melting shop with three 250 ton capacity basic open hearth furnaces working the hot metal process. The Colville group was now a large organisation operating a total of forty-eight open hearth furnaces with capacities in the range 60–350 tons in its six principal steelworks.

In 1956, Sir John Craig ended his 39 years as Chairman of Colvilles. He was succeeded by Sir Andrew McCance who, for 25 years, had had a major influence on the technological development of the company.

Product Diversification

One important factor that was changing the market for steel was the increasing sophistication of the engineering industry. Whereas, pre-war, Colvilles' output of plates and sections had overwhelmingly consisted of mild steel, there was a rapidly increasing demand for steel with enhanced properties. For many years the company had been the principal UK producer of large boiler quality plates for the fabrication of pressure vessels, marketing a range of special steels for service at sub-zero, atmospheric and high temperatures. This market became progressively more challenging as engineers sought higher strength steels suitable for fabrication by welding. The group metallurgical department, formed in 1940, had become very much involved with the problem of brittle fracture of ship plates. Now, as the Central Research Department, it expanded in order to develop steels to meet these new marketing requirements and Colvilles adopted its advertising slogan 'fitness for purpose steels'. Research was also undertaken on various production problems in an attempt to increase yields, reduce the incidence of defects and increase productivity.

Colvilles continued to develop its central mechanical and electrical departments, which were capable of handling all major plant development projects. The group established an engineering works at Mossend that could manufacture much of the new plant that was required.

Nationalisation of the industry in 1951 had had virtually no effect on the organisation or day to day running of Colvilles, but the increasing involvement of the Government in industrial development had very significant consequences. This involvement continued after the industry was de-nationalised in 1955. Colvilles had survived bad times and thrived in good times by adopting conservative development policies, spending money carefully on projects which were conducive to plant efficiency. The Government wanted an increase in the production of steel sheet, and the construction of a new strip mill was under discussion.
In 1956, Colvilles came under pressure from the Government to proceed with a major development programme to build a strip mill at the Ravenscraig works. Colvilles was unwilling to do this for several good reasons. There were not sufficient coal supplies for the increased iron output or sufficient assured supplies of steel scrap. There was no local market for strip steel and the project would be uneconomic. However, the Government felt that social and political issues were paramount and eventually Colvilles agreed to a scheme which involved them becoming involved in large scale strip production with a substantial loan from the Government. The scheme involved construction of a third blast furnace at the Ravenscraig works and augmenting steelmaking capacity with a fourth open hearth furnace and a number of LD oxygen blown converters. There would be a slabbing mill, and light plate and strip would be produced in a semicontinuous mill. Cold reduction would be carried out in a four stand, four high tandem mill, to be constructed at the Gartcosh works. This ambitious scheme was completed and in operation in 1963. Unfortunately, this coincided with a downturn in shipyard orders and an increase in the price of coal and Colville's worst fears about the uneconomic nature of the whole project were realised.

Otherwise, the affairs of Colvilles thrived. The Central Metallurgical Research Department, with a staff of over 200, had developed a wide range of special steel products including stainless and nickel clad plates, quenched and tempered steel plates and sections, wear resisting steel plates and a range of weldable notch tough steels for structures and pressure vessels. Colvilles was a major supplier of special quality plates to the nuclear power industry and for naval construction. Corten corrosion resisting steel was produced under licence from United States Steel Co., and Fullwood Foundry was producing spheroidal graphite iron castings.

Valediction

The financial problems consequent on the construction of the Ravenscraig strip mill were resolved by re-nationalisation in 1967, but in many other respects the managerial changes that followed were disastrous for what had been the Colvilles Group. The works, which had been developed as coordinated units under a system that gave them a high degree of autonomy while being under the control of a central planning board, found themselves under the control of a number of different divisional organisations. The central organisations, Commercial, Engineering and Metallurgical Research, which had helped the company to flourish, could no longer play their hitherto effective role. The result, for the Scottish steel industry, is an unhappy story.

Colvilles had served Scotland and its industry well for over a century. Its success in establishing itself as the dominant Scottish steel producer may be attributed to the following factors:

- planning and operational control being continually in the hands of 'steelmen', each with his own area of specialist knowledge, be it finance, technology, engineering, metallurgy or production management
• conservative financial management
• good relationship between management and the whole workforce, probably related to the fact that the men at the top were characterised by having a ‘social conscience’.

DANIEL DONCASTERS

BY R. FENN

Daniel Doncaster, the company founder, was born at Mapelbeck, Nottinghamshire in 1756 into a Quaker family of soap-makers. His father Samuel moved into Sheffield, establishing a grocery shop, and Daniel was apprenticed to George Smith, a file-maker. In 1778 Daniel established himself as a ‘little mester’ file-maker in premises close to where he lived in Allen Street, initially selling his products as a ‘journeyman’, sometimes travelling long distances to supply his customers. On 29 May 1778, his trademark (see Fig. 3) was granted by King George III, the fee being established at 2d, payable each Feast of the Pentecost. Daniel also marketed pure Swedish iron from Leofsta, whose trademark is shown in Fig. 4 (the company continuing to market these irons until 1898).

During the founder’s lifetime, his two sons William and Daniel entered the busi-

Fig. 3 Daniel Doncasters’ 1778 trademark.
ness, continuing it on his death in 1819, although not prospering greatly. In 1829, they formed a partnership as file manufacturers and steel converters (i.e. converting wrought iron to cemented steel), investing £1000 each in the business. Nine months later Daniel invested a further £200 and their mother £250. At this stage, virtually the whole of their steel was cemented from Swedish iron, which came via Hull on the East coast, but between 1829 and 1833 the partnership purchased £50 worth of steel from Benjamin Huntsman of Attercliffe. During the time of the partnership, Daniel built offices and a warehouse (for steel) and a converter on Doncaster Street. 1831 saw the cementing of pure Swedish irons with charcoal to produce ‘blister’ steel, used for rasps, knives and scythes and as charge for the crucible melters in Sheffield. (One of the cementing furnaces remained in use until after 1939 and eventually the BISRA cutlery section was established near it in 1951.) Between 1831 and 1833, all Doncasters’ steel melting was undertaken by Drabble and Sanderson, a local company, while tilting and rolling was undertaken by the Philadelphia Tilt Co. and Philadelphia steelworks.

In 1832, the partnership between William and his younger brother Daniel was dissolved (by Daniel) immediately after stocktaking. Assets were divided equally between the two, but Daniel left his share (files worth £1000) with William to sell on his behalf, Daniel continuing as a steel converter and refiner. His profits from his first year alone were £250, and he continued making and selling blister steel until 1862 (in 1857, the company name had become Doncaster Steels Sheffield), when Daniel Doncaster & Sons was formed, which marked the end of the blister steel era of the company’s history.

Business directories of the time quote the company being Merchants, steel converters and refiners with addresses in Doncaster Street and Copper Street. Other
residents of Doncaster Street were quoted to be iron founders and cutlery manufacturers, while nearby residents on Copper Street were scissor, file, razor and cutlery makers. This appears to be an early example of the modern business paradigm of siting production near end users to save transport: *plus ça change!*

1865 saw the building of three crucible furnaces on the Doncaster Street site and increasing profitability. Soon afterwards (1870) Daniel Doncaster & Sons began selling alloys to the local iron foundries. Samuel’s brother-in-law Herbert Barber joined the company in 1876, his eldest sons beginning to merchant rare earth metals for steelmaking and iron founding through the company. This year also saw the first order for Vasa Swedish steel from the company, a liaison that was to last for about 100 years. Swedish Bessemer steel (exceptionally low in sulphur) was merchanted through Doncasters to the Sheffield industry in 1881, where it found an immediate use for making tools and tool steels, becoming by 1883 the predominant material. In 1892 the company expanded its range to include the supply of nickel, spiegeleisen and then ferrochrome, ferrovanadium and tungsten to local steelmakers. By special arrangement, Doncasters sold ‘crucible ready’ charges containing salammoniac (as a flux) and sieved spiegeleisen to the local steelmakers. Thus Doncasters was quietly influential in the developments in crucible steelmaking. Simultaneously with selling crucible ready steel charges, Doncasters also sold one of the crucible steel’s main competitors, razor steel, from Sweden, thus winning whichever way the local industry went! By 1898, the costs of forging Swedish steel were uncompetitive using hired plant, so Doncasters took the decision to purchase a small forge and to re-equip it with steam hammers of up to 5 tons weight only for the Swedish steel. This site, on Penistone Road, had been the location of forging operations since 1637, when water hammers were used. (Essentially, this move marked the company’s departure from the craft tradition of each workman responsible for all the tasks from melting through to forging.) A new twenty-four hole crucible furnace was built on a new site in Hoyle Street, after three old six hole furnaces (in Doncaster Street) were demolished. Doncasters’ business continued to thrive, for as the century turned, the forge continued to grow with demand for alloy steel components.

1902 saw the company name change from Daniel Doncaster & Sons to become a limited company. A serendipitous event in 1907 gave rise to an important relationship between Doncasters and Martino Steel in Birmingham. It began with the misdirection of a letter to the same address but in Sheffield. Occupying the address in Sheffield was Turners, who realised the mistake and forwarded the letter to Martino Steel with a note saying that it (Turners) could supply the steel die blocks. Martino received the original (misdirected) order and re-ordered from Turners, who then ordered the steel from Doncasters. This initiated the relationship between Doncasters and Martino and led the former to open a heat treatment facility, this time on Rutland Road, specifically for the heat treatment of Swedish steels. In the same year (1911), Doncasters supplied alloy steels, under the brands of MNO & CVS, to Martino Steel for the motor and allied trades. When, in 1912, the aircraft engine manufacturers Gnome-et-Rhone asked Doncasters to quote for poppet
valve manufacture, it modified a tool steel, drop stamped the valves from this steel and won the order, beginning the supply of valves in the same year.

With the start of the First World War, Doncasters, through its Martino link and its drop stampable valve steel, was drawn into the supply of components for the car, lorry and bus fields. For the duration of the war, the company, unlike other Sheffield steel companies, did not get involved in armaments manufacture, choosing to keep its involvement, rather, with tool steels. At the end of the war, Doncasters became a founder member of the Drop Stamping Association, based in Sheffield, as a result of all the experience gathered. This signalled the effective end of the second phase in the company’s life, that of the move from steelmaking to steelworking.

In 1920, the United Steel Companies bought all of Daniel Doncasters’ ordinary shares and thus took control of the company, although Samuel Doncaster remained as chairman and the family connected remained. Doncasters formed an association with Vauxhall motors (via the Drop Stamping Association), which was maintained until 1978. Doncasters also began valve forging, which was to become an important business activity. Its expertise in high quality valve manufacture gained the company the contract to supply Rover cars with silchrome valves, undercutting the previous supplier of ‘ordinary’ steel valves by $d. Within the United Steels Group, Doncasters’ development continued, until the retirement of Samuel Doncaster as chairman of the board, although he remained a board member (1931). His replacement was Harry Doncaster, although the heaviest board loads were carried by Basil Doncaster, Charlie Doncaster and Reginald Steel (the general manager, a USC appointee to the board). 1931 marked the 50th anniversary of Doncasters supplying Swedish Bessemer steel to the Sheffield tool trade, where it had become the base of most cheap tool steels. But the Doncasters development was halted by the Great Depression, lasting from 1931 to 1934, when financial reconstruction of the company was advised. Then in 1936, USC disposed of its interests in Daniel Doncasters and the company was reformed, again falling under control of the family.

Horizontal upset forgings were the next arena into which Doncasters stepped (in 1937), beginning commercial production later that year. The heavy stamping shop was modernised with the installation of the first double acting stamping press in the UK. This was used to make stampings for the motor car, lorry and aeroplane industries. Next door to the heavy stamping shop, a light stamping shop was built and laid out on linear flow principles, producing valves and light stampings in austenitic stainless steel, valve forgings and light stampings. At this stage (1938), Daniel Doncasters employed some 900 people, yet still managed to retain the character of the founder. Immediately before the war, the board consisted of: James Henry Doncaster (Chairman), Charles Doncaster, Basil Doncaster, James Henry Wilkinson, Ronald Steel, George Coop and Percy Hemingway.

Just before the start of the Second World War, the firm was developing new processes that were to contribute directly to the war effort. Co-operation with Thompson Products (of Cleveland, Ohio) led to the installation of National
Maxipres forging machines on the Penistone Road site and the production of the first extruded valves made outside the USA. Further co-operation with Enwood Steel Products led to the manufacture of valve springs from Swedish steel rod to fulfil demand from Rolls-Royce, Vauxhall, Morris, Standard and Ford. During the war, Doncasters produced components for Rolls-Royce and Bristol aeroengines, Vauxhall and Leyland vehicle components, plus forged connecting rods, rocker arms, propeller hubs and gears. In March 1941, Doncasters began to produce aircraft valves on the Maxipres machine, while in July 1943 trials of forged silchrome steel valves began. An internal management memo from 1944 stated that, after the war, the future was with the younger men, but led by the older men, and detailed management changes to this end. Before the end of the war, Doncasters increased in size with the installation of a second valve press and a second upset machine. New Victoria Forge was built as a fully mechanised ingot cogging shop. Both the closed die and multi-stage forges were increased in size and production rate, while rolling and machine shops were scheduled, but never laid out. During 1946 and 1947, Rolls-Royce began to place orders for 'odd-shaped bits' of nickel and nimonic stampings of gas turbine engines, which marked the beginning of the fourth phase in the history of Daniel Doncasters as a sequential company history. To develop the technology in this field of new nickel based alloys, Doncasters increasingly co-operated with nickel specialists Henry Wiggin Co. Ltd (this relationship was to have a profound effect on Daniel Doncaster & Sons in future years). These years mark the first time that Doncasters had worked any non-ferrous materials, and, consequently, the fourth phase was one of increasing working of non-ferrous materials and decreasing working of steels, on which the firm's reputation had been founded.

In 1951, returning to an older status, Daniel Doncaster & Sons became a limited company once more. That same year, it purchased Monksbridge Iron & Steel Co. in Leeds, which became the site of all Doncasters' turbine blade manufacturing. Turbine blade manufacture proved to be the stimulus for the purchase of Moorside (in Oldham) as a site for the machining of turbine blades; Pilgrim nuts (built in tensioning and releasing systems) were also made at Moorside, only the third time in its 178 year history that Daniel Doncasters had made an end product. Blaenavon Iron & Steel works were bought in 1957 to supplement the Penistone Road site for the manufacture of traditional hammered products, but also with a view to having another site on which turbine blades could be made. Blaenavon works is a metallurgically historical site, where Thomas performed the first basic Bessemer steel-making experiments in early 1878.

In line with post-war expansion plans, the original Doncaster Street site was closed and taken over by the British Iron and Steel Research Association (BISRA) laboratories (Fig. 5). BISRA was officially opened on 11 November 1953. Next to the BISRA cutlery laboratory stood one of the old Doncasters' cementation furnaces, last used in 1951.

In 1955 Basil Doncaster retired as Chairman and was replaced by Reginald Steel; Richard Doncaster became MD. It is widely acknowledged that it was due to Basil's
forethought that the company had been returned to family control in 1936. Still, in 1955, the company letterhead advertised its business in Swedish iron and steel and, unlike many of its local competitors, it had no company wide planned training programmes. Company training was organised on the basis that 'each man perform a responsible job while receiving regular support not only from Departmental heads, but also five executive directors’, not a programme conducive to taking technological development forward at the pace needed.

By the New Year of 1958, the existing premises at Penistone Road were inadequate to deal with the laboratory requirements of producing aerospace components, so the group moved its headquarters and laboratories to Birley House, on the outskirts of Sheffield. This move allowed the Penistone Road site to install a second mechanical forge alongside the Victoria forge, which included new presses, new die shops, billet shears and a 1500 ton hydraulic cogging and forging press. As the 1960s opened, Doncasters along with all the other Sheffield steelworks felt optimistic, and new markets were emerging to be conquered. This was first felt in 1962, when Doncasters supplied open die forgings for pipe flanges to John Brereton, which were used in oil rigs and petrochemical plant and made in a wide range of compositions from simple carbon steels to corrosion resistant alloys. Then, two years later, Doncasters formed a joint venture company with Hadfields (Doncaster-Hadfields), to operate in Australia. Hadfields, which had once been the powerhouse of the Sheffield steel industry, was in slow, long term decline and the joint company did not prosper, repaying neither parent company much of their investment.

At the beginning of the 1970s, the Doncaster group employed 4000 people, 1500 each on the Monksbridge and Penistone Road sites. Whittingham & Porters, a Hull
based drop stamping company, was acquired in 1973. Monksbridge installed a
14,000 ton press for turbine blade manufacture in 1974 and the same year saw
Dudley-Fosil, of Wright Hingley, brought into the group to supplement the ability
for ring rolling. In the following year, the growing association with nickel alloys,
initiated in 1946 with Henry Wiggin, came to fruition when International Nickel
(Inco) bought Daniel Doncasters out. While the company still had some control of
its future (before 1979), the Daniel Doncaster group within Inco consisted of: Daniel
Doncaster Head Office & Laboratories (Birley House), Doncasters Sheffield Ltd,
Doncasters (Monksbridge) Ltd, Doncaster Moorside Ltd, Doncaster Blaenavon Ltd,
John Brereton Ltd, Hingley Rings Ltd, Whittingham & Porters Ltd.

When Richard Doncaster retired in 1979, the last link with the founding family
was severed and the company transferred fully into the Inco group. However, in
1997, a new group ‘Doncasters’ demerged from this group, with 3700 employees on
twenty-two sites across Europe and North America. Penistone Road was still one
of the new company’s operational sites and the next year, the new company cel-
ibrated the 100th anniversary of the original purchase of the site by Daniel
Doncasters. Whether this new company represents the fifth (or is it the sixth?)
phase in an ongoing company history is debatable. What is probable is that the
influence of Daniel Doncaster, which inhabited the company that carried his name,
has not survived into this reincarnation as ‘Doncasters’. Although, perhaps the
whirring of all those turbine blades has not totally dissipated the spirit of the
founder!

DORMAN LONG AND CO. LTD

BY C. BODSWORTH

This company played only a very minor role in the early growth of the iron and
steel industry in the North East of England. Through the acquisition of other
companies, which had strongly influenced that early growth, however, and by the
construction of new works, it grew to become the dominant steelmaker in the
region. In terms of output, when the industry was nationalised in 1967 it was
the sixth largest producer in the United Kingdom.

In contrast to the sustained growth of the ferrous industry in South Wales, the
Midlands and Scotland throughout the nineteenth century, the North East region
remained largely undeveloped until the 1850s. This seems surprising in view of the
copious quantities of excellent coking coals which were available locally from the
Durham coal mines. The production of steel by cementation of Swedish bar iron
had prospered during the eighteenth century in the vicinity of Newcastle-upon-
Tyne, but this trade had declined in the face of competition from other locations. A
few small blast furnace plants struggled for survival in the early 1800s along the
banks of the rivers Tyne and Wear. There was negligible industrial activity in the
vicinity of the river Tees. The population of the area which was to develop into Middlesbrough, the centre of the industry, was less than thirty in the first decade of the nineteenth century. The two blast furnaces in the North East of England produced only 2500 t of iron per annum. Teesside began to achieve some prominence in 1830 when Edward Pease and partners bought 500 acres of land, including salt marshes bordering the river, on which they built a wharf for shipping the Durham coal.

The situation changed rapidly when massive seams of low grade phosphoric iron ore were discovered in the Cleveland hills. The first quarry was opened in 1837 and the Wylam Iron Co. opened the Grosmont mine two years later. The major development of the seams started in 1850. Within 15 years the Teesside region had become the largest centre for iron production in the world. The decline from this peak position had just started when the Dorman Long Co. was formed. Two publications provide a detailed account of the history and development of the industry in the Cleveland area and more specific information about the growth of the company.

Arthur Dorman and Albert de Lande Long formed a partnership in 1875 to lease the West Marsh Ironworks in Middlesbrough. The works, with twenty puddling furnaces, had been closed down during the 1873 depression. The partners started to build up a trade in the supply of wrought iron bars and angles for the newly developed local shipbuilding industry. Four years later they leased Sir Bernhard Samuelson's Britannia works, which was on an adjoining site, to expand the production of wrought iron. This works, which contained 120 puddling furnaces, forges, hammers and bloom and rolling mills, had also closed down during the depression.

In 1883, a start was made in the development of what was to become one of the company's major activities, when wrought iron structural girders were first produced at the Britannia works. Bypassing the Bessemer process, half of the puddling furnaces were replaced by acid open hearth furnaces in 1886 to facilitate the production of steel girders. A constructional and bridge building department was opened in 1890. The international reputation that the company acquired rose mainly from the activities of this department in the 1920s and 1930s when twenty-eight major bridges were constructed, including the Sydney Harbour bridge in Australia, the Tyne road bridge in Newcastle and crossings over the Nile and the Thames.

The status was changed to a limited liability company in 1889, with an authorised share capital of £350,000. The total steel output in that year was 100,000 t. Trials were started in 1894 to develop a basic open hearth practice which could be used with iron produced from the Cleveland ores. The basic process was not operated on a large scale until after 1900, but the capacity was then more than doubled to about 400,000 t per annum by 1908. The company also started to diversify, with the acquisition in 1898 of the Ayrton Sheet Works and the Cleveland Wire Mills.

In the early years of the twentieth century the ferrous industry was severely affected by a world excess capacity for steel production. This was exacerbated in
Britain by the Government's adherence to the free trade principle and the consequent dumping of steel in the UK by overseas competitors. Dorman Long were unable to pay a dividend for a number of years, but the company suffered less during this period than many of its competitors. Two of these, Bell Brothers Ltd and the North Eastern Steel Company Ltd, were acquired by Dorman Long in 1902-1903. Consideration of the history of these two companies and of the works of Sir Bernhard Samuelson and Bolckow Vaughan Ltd, which were absorbed at later dates, facilitates a more meaningful appreciation of the development of Dorman Long.

Bell Brothers Ltd

Isaac Lowthian Bell was one of the outstanding entrepreneurs in the UK during the nineteenth century. His father was a joint owner with Messrs Losh and Wilson of the Walker Iron Works on the river Tyne. In 1844, I. L. Bell designed a blast furnace at the works for the smelting of the newly discovered Cleveland ore. In the same year, with his brothers John and Thomas, he took over the lease of the Wylam Iron Works with one blast furnace, also located on the Tyne. When a satisfactory process had been developed in these furnaces for smelting the Cleveland ore, Bell Brothers built the Clarence works on the north bank of the river Tees. Construction started in 1853 and the plant was remarkable for the height (18 m) of the blast furnaces, which were built with closed tops. Lowthian Bell acquired an international reputation for his design and operation of the furnaces. Six blast furnaces were in use by 1865 and two more had been added by 1876. The iron was refined in a battery of puddling furnaces and Lowthian Bell was actively involved in attempts to mechanise the process. In 1878, he reported his attempts to dephosphorise iron in a rotary puddling furnace. His achievements were recognised when he was elected as the third President of the Iron and Steel Institute in 1873, following Sir Henry Bessemer in that role.

Half the shares in the company were acquired by Dorman Long when the status was changed to a public liability company in 1899. Three years later, when dumping of semi-finished steel drastically curtailed the order book, the remaining shares were acquired from the Bell family in exchange for Dorman Long shares.

Sir Bernhard Samuelson and Co.

Samuelson, who owned a foundry producing agricultural machinery at Banbury, Oxfordshire, built the South Bank Iron Works with three blast furnaces near Eston on the river Tees in the period 1853-1855. The works was sold in 1863 and the proceeds were used to build the Newport works further inland but still on the Tees. Two large blast furnaces were built initially and three more were added at the end of the decade.

Samuelson was one of the first ironmasters to collaborate with William Siemens in the development of the acid open hearth process. Extensive trials were conduc-
ted at the Newport works in the late 1860s, but they failed to resolve the problems which were preventing full scale production. Commercial exploitation of the process had to await the outcome of Siemens’ experiments in his own Landore, Swansea works. Meanwhile, Samuelson decided to develop the production of wrought iron and in 1871 built the large battery of puddling furnaces at the Britannia Iron Works. Sir Bernhard sold out and retired in 1872. Two years later the decline in the demand for wrought iron with the growth in steel output, exacerbated by the depression, led to the closure of the Britannia works and the plant was dormant until it was eventually taken over by Dorman Long. The Newport works continued in production and grew steadily in output, with many innovative developments. The first British Otto vertical flue and Simon Carves coke ovens with byproduct plant were erected on the site in the late 1890s, at a time when most of the coke produced in Britain was still made in beehive ovens. The works was bought by Dorman Long in 1917, by which time there were eight large blast furnaces installed on the site.

Bolckow Vaughan and Co. Ltd

Henry Bolckow acquired considerable capital by speculation in the grain market. John Vaughan started his career at the Dowlais works in Merthyr Tydfil, South Wales and was manager of the Walker Iron Works owned by Bell, Losh and Wilson when he entered into partnership with Bolckow in 1839. The partnership flourished and the company became the pacesetter for developments in iron and steel manufacture during the second half of the nineteenth century. It was a major contributor to the total ferrous metal output from the region up to the time of the merger with Dorman Long in 1930.

The Middlesbrough Iron Works, built by the partners on the south bank of the river Tees, was the first major industrial development in the Middlesbrough area. A foundry and machine shops were built to manufacture steam engines and agricultural equipment. A rolling mill started to produce wrought iron rails in 1841. Pig iron was initially delivered to the plant by sea from Scotland, but in 1846 the Witton Park works at Bishop Auckland was built with two blast furnaces, rolling mills and puddling furnaces to process local coal measure iron ores and supply wrought iron for the Middlesbrough plant. The limited availability of the ore deposits, however, led to the discovery and development of the Cleveland iron ores. The Skinningrove mine began to supply the Witton Park furnaces in 1848 and the Eston mine followed suit in 1850. With the development of its own ore supply, the company built furnaces nearer to the ore beds to expand production. Three blast furnaces were erected at the Middlesbrough works in 1852 and a new works with six blast furnaces was opened nearby at Eston in the following year. One of the Witton Park blast furnaces was rebuilt to twice the original size in 1858 and this was the start of the trend to build very large furnaces in the region.

The demand for wrought iron products was increasing rapidly and the company’s sales were increased by the installation of a plate mill at the
Middlesbrough works to supply wrought iron ship plate. Additional puddling furnaces were built at Witton Park and at Middlesbrough to meet the demand. By the early 1860s, seventy-one puddling furnaces were in use at Witton and sixty-eight at Middlesbrough. Unfortunately for the company, the demand for wrought iron now began to fluctuate markedly from year to year. In 1875 all the company's puddling furnaces were closed down during one of the periodic recessions. The trade in wrought iron never fully recovered after this time, for the Bessemer and open hearth processes were now producing bulk quantities of homogeneous metal with greater strength than that of wrought iron.

John Vaughan died in 1868. He had appointed as his successor Edward Williams, who had also trained at the Dowlais works in South Wales. Williams was aware of the attempts being made to apply the acid Bessemer process in Wales and decided that the company should adopt the process. The Gorton Steel works near Manchester, containing two 5 t Bessemer converters and a rail mill, was acquired from the liquidators of the Lancashire Steel Co. and used to gain experience in the operation of the process. The plant was not profitable and was sold five years later, but the potential offered by the process had been confirmed. A new Bessemer steelworks was erected on part of the site of the Eston ironworks with four 8 t acid converters feeding a rail mill. Hematite pig iron was supplied by three new blast furnaces at the Eston plant, the ore being delivered directly into the works via a wharf on the Tees from mines in Spain, which the company had started to develop in 1873.

The new steelworks commenced production in 1877. In the same year Sidney Thomas and Percy Carlyle Gilchrist, working in South Wales, took out their first patent for the conversion of phosphorus rich pig iron into steel in the converter. Windsor Richards, a Welshman who had worked at the Dowlais and Ebbw Vale plants, had succeeded Edward Williams as general manager. Richards visited Wales to examine this new work. Recognising the potential of the development, he invited Thomas and Gilchrist to continue their experiments at the Middlesbrough works, where two small converters were provided for their use. The former chief chemist of the works, J. E. Stead, joined in the experiments and identified the need for the afterblow for phosphorus removal. A satisfactory basic refractory lining was developed for the converter, the first official blow was completed on 4 April 1879, and the complete process was described in an 1879 patent.

The four acid converters continued in use. Two 15 t basic converters were installed in a new melting shop at the Eston works, giving an annual capacity for 100,000 t of steel. Two more 15 t converters were commissioned in 1881 and a third pair in the following year, increasing the capacity to 230,000 t. All the converters continued in use until they were replaced by open hearth furnaces in 1911–1913.

By the end of the nineteenth century the company had achieved prominence as the largest manufacturer of iron and steel in the North East region. This had been accomplished both by the development of its own works and by the purchase of other companies. In 1899 the Clay Lane Iron Co. was acquired. This works which was opened in 1855, had been developed under the guiding hand of Thomas, the
son of John Vaughan. Six blast furnaces were in operation in 1871 when he sold the plant. Two years later it was described as the largest ironworks in the world, but the owners were bankrupted by poor trading conditions in 1876. After a chequered history, the works was finally brought under the control of Bolckow Vaughan. Other acquisitions included the Darlington Rolling Mills Ltd and Eston Sheet and Galvanising Co. Ltd. Purchase of Redpath Brown Constructional Engineers Ltd in 1923 extended the activities into a field which was becoming dominated by Dorman Long.

Bolckow Vaughan was not isolated from the boom and slump conditions which plagued the industry from the latter part of the nineteenth century. The demand for railway rails began to decline rapidly soon after the basic Bessemer melting shop was completed. A depression in the local shipbuilding industry resulted in closure of the plate mill for three years from 1902. Additional basic open hearth furnaces and rolling mills were constructed during the First World War, but production was again curtailed in the face of dumping of semi-finished steel by overseas competitors in the 1920s. Even so, the industry was shocked to discover the magnitude of the financial problems facing the company at the end of the decade. The merger with Dorman Long in 1930 was imposed by the Bank of England as a condition for the provision of a financial loan to allow the works to continue to operate.

North Eastern Steel Co. Ltd

The company, which was formed in 1881, was the only other works in the Cleveland region to use the basic Bessemer process. Sidney Thomas was one of the directors. The first melt was made in 1883 and the capacity had reached 100,000 t/year with the installation of four 10 t converters in 1885. The steel was rolled into rails and into angle beams for shipbuilding. No blast furnaces were provided. The charges were melted in a battery of cupolas, using bought-in pig iron, to which puddlers cinder was added initially to enhance the phosphorus content.

The dumping of imported steel which caused the demise of Bell Brothers Ltd had a similar drastic effect on North Eastern Steel and the company was taken over by Dorman Long in 1903. The Bessemer converters continued to be in use until 1919, when they were replaced by open hearth furnaces.

Dorman Long in the Twentieth Century

The recession in the heavy steel industry during the first decade of the twentieth century affected the company less than many of its competitors. The dividends paid on the company shares were spasmodic and very low, but funds were found for the modernisation of the Britannia and Clarence works. With the return to more prosperous conditions at the end of the decade, the company had reached the dominant position in the region with an annual capacity of 400,000 t of steel. Subsidiary companies were opened in South Africa and Australia.

To meet the demand for increased production during the First World War, the
works of J. Walker Maynard and Co. at Redcar was acquired in 1916. With the aid of a £1 million loan from the Government a start was made on the construction of a vast new works with two blast furnaces to produce 4000 t of iron per week feeding a mixer and 10 open hearth furnaces, and universal, plate, and cogging mills. The rolling mills were not fully operational until 1919, after the end of the war, and the melting shop was completed in the following year, when the company raised an extra £3 million capital through the sale of shares to repay the loans taken out to cover the construction costs. The Betteshanger colliery in Kent was purchased in 1917 to secure fuel supplies for the new works.

In anticipation of a postwar boom, the Carlton Iron Co. at Ferryhill, County Durham was acquired in 1920. This company operated three blast furnaces, with coke ovens supplied from its own colliery. It also owned the Motherwell Iron and Steel Co. in Scotland. The Ayrton sheet rolling mills were modernised. A large new blast furnace, capable of producing 2500 t of iron per week, was blown in at the Clarence works in 1923. But the boom conditions did not materialise. There was negligible new investment through the 1920s, although capacity increased steadily to reach just under 1 Mt by 1929.

Dorman Long was also facing financial problems when the Bank of England induced the merger with Bolckow Vaughan in 1930. A programme of rationalisation followed the amalgamation and the Carlton, Newport, and Clarence works were closed down during the next four years, but the company narrowly escaped being forced into receivership in 1934.

As trading conditions began to improve in the 1930s the Redcar blast furnaces were modernised and all plate manufacture was concentrated on this site. Extensive rebuilding was also started at the Cleveland works, with the reconstruction of two blast furnaces and the addition of a third furnace plus one more 100 t open hearth furnace and a light section mill. The alterations had not been completed when the Second World War started in 1939. At that time the company was still operating four steel works, Acklam (semis), Britannia (sections), Cleveland (billets, joist, rails), and Redcar (plates), with a total output of about 1.25 Mt of finished and semifinished products. Very few plant changes were made during the war and the total output remained of the same order when the war ended in 1945.

The low grade Cleveland ore deposits were becoming progressively more expensive to extract from the ground as the seams were followed to greater depths. Vast quantities of much higher grade deposits were beginning to be exploited overseas, which could be imported in the new bulk carrier shipping at a competitive cost. With the return of peace, therefore, an ore receiving terminal was developed capable of unloading 15,000 t bulk carriers, on the south bank of the Tees, adjacent to the Cleveland works, to handle up to 1.5 Mt of imported ore and 0.5 Mt of Cleveland ore per annum. A sinterplant to produce 8000 t/week was installed on the site and a second machine was commissioned in 1949.

The first round of nationalisation of the industry in 1951 had no significant effect on the company and it was returned to private ownership two years later. A site had been acquired at Lackenby in 1943 with the intention of building a new works.
Construction was delayed, but the open hearth melting shop finally started production there in 1953. The five furnaces were each capable of producing over 4000 t of ingots per week. Billet, bar, ore and strip mills were installed and the first British universal wide beam mill was commissioned in 1958. A coil plate mill was also installed. Iron was supplied from the adjacent Clay Lane works, where three large furnaces were built to replace all the older furnaces. Further rationalisation followed. The Redcar blast furnaces and the cold metal melting shop at the Britannia works were closed down. Some of the Cleveland works open hearth furnaces were also demolished, making room for the installation of two electric arc furnaces.

In 1965 the total output of the company was approximately 2 Mt of finished steel per annum. This was well in excess of the threshold set by the Government as the criterion for renationalisation and the Dorman Long name was consigned to history when the company was taken into state ownership in 1967. The Teesside works became part of the BSC General Steels Division. The Lackenby plant continues as the principal production unit in the region, with three LD converters feeding the continuous casting plant. A new ore terminal handles imported ore at Redcar. The last Cleveland iron ore mine was closed in 1964.

EDGAR ALLEN AND CO. LTD

BY C. BODSWORTH

In terms of tonnage output this firm was one of the smallest of the British steel-makers, but it came high on the list when ranked in terms of the value per tonne of the products. It became well known for numerous achievements and particularly for the introduction to Britain of three important developments in steelmaking technology. A magazine entitled *Edgar Allen News* was produced, initially bimonthly in 1919 but then monthly until publication ceased in December 1966. It had a large readership, especially during the last two decades of its life when a number of textbooks written by the chief metallurgist, Dr Edwin Gregory, and the editor, Eric Simons, were serialised. Some of the information presented in this article was derived from the magazines.

The founder of the company, William Edgar Allen, was born in England in 1837 and was a direct descendant through the maternal line of a wealthy Rudelhoff family, who escaped from Russia when their estates were confiscated in the eighteenth century. He was educated in Paris and travelled extensively on the Continent. At the age of twenty-five he began to utilise the knowledge gained from his travels when he was appointed continental sales representative for one of the specialist Sheffield tool steel manufacturers. This led in turn to an interest in the manufacture of tools.

Edgar Allen set up his own company in 1868 in small premises in Joiner Street.
in the centre of Sheffield to produce engineer's tools. Most of the famous Sheffield steelmakers were already well established by that time and had moved to large factory sites to the east of the town when a railway line was opened adjacent to the canal. But Sheffield had only recently started to achieve supremacy over the Birmingham area as the centre for the production of files, saws, and other cutting tools and several new companies were starting tool production on sites in and around the city centre. Shortly afterwards he formed a partnership with George Rose Jones and leased a small works in Well Meadow Street to produce tool steel, hand cut files and circular saws. The partnership was terminated in 1883, by which time the works employed 50 people. In the following year an office was rented at 124 Saville Street in the east end of the city and a crucible steel melting shop was rented in Bridge Street, near the city centre, to increase the production of tool steel. Within three years, this additional plant was unable to provide the tonnage required to meet the growth in orders and the Minerva Works in Cross George Street was bought out to increase steel production. The company was finding a strong demand for its 'tungsten self-hardening tool steel which does not require a water quench'.

With three partners, who joined him from a rival steel manufacturer, Samuel Osborn and Co., Allen formed a private limited company in 1890 with an authorised capital of £100,000. Construction of a large steel foundry and tool factory was started on the site of an old railway wagon works at Turnpike Lane in the Tinsley district of Sheffield. The plant was named The Imperial Steel Works and this remained as the home base of the company throughout its independent existence.

The steel for the foundry was melted initially in a Roberts converter but this proved to be inconsistent and unreliable in operation so it was replaced by a Tropenas side blown converter, the first of this type to be installed in a British works. An early success was the production of cast steel dynamo magnets, which had previously only been available in wrought iron. The satisfactory results obtained with the Tropenas vessel soon led to the widespread adoption of this technique by the steel foundry industry. The Minerva works was sold and all steel-making was concentrated at the new site, where output increased rapidly. A new file shop was opened at the Imperial works in 1894.

Many British steelmakers opened subsidiary companies overseas in the period from about 1890 to 1910. Edgar Allen followed the trend and development overseas started in 1894 with the opening of a South African branch in Johannesburg. The status was changed to a public limited liability company in 1895, with an authorised share capital of £350,000. The increase in the value of the assets is indicative of the rapid growth which had occurred in the previous five years. The company now employed about 400 people. A metallurgical laboratory was opened in 1898 to deal with the increasingly specialised nature of the products. A good trade had been established in the production of castings for railway locomotives and there was a growing demand for wear resistant castings. Manganese steel had already been proven satisfactory for this purpose and by the end of the century the foundry was producing castings containing 12-14%Mn. This led to the acquisition
in 1903 of the Yorkshire Steel and Engineering Works as an outlet for 'Imperial Manganese Steel', for this company specialised in the production of crushing and grinding equipment, conveyors and tramway trackwork. The Imperial works had now grown in size from the original 2 hectares to occupy 9.3 hectares. Expansion overseas also continued with the opening of manufacturing facilities in Chicago, IL, and at Riga, then in Russia. These branches did not survive for more than a decade, the former plant closing in 1920 and the latter in 1916.

The second major development in steelmaking methods introduced by the company was the commissioning in 1910 of the first Heroult electric arc furnace in Britain. The 3.5 t furnace increased the capacity for the production of castings in alloy steels and the company had soon perfected a two stage oxidation-reduction refining procedure to make steels with low phosphorus and sulphur contents. In 1912, however, the company was granted a patent for the production of rolled manganese steel railway and tramway rails and the demand for these products soon outstripped the melting capacity. Consequently, a duplexing practice was introduced in 1913, the charge being melted, decarburised and dephosphorised in an open hearth furnace, then transferred to the electric arc furnace for deoxidation, desulphurisation and alloying. Tap to tap time was 4 h in the arc furnace. Since the company did not possess appropriate rolling facilities, in the same year an arrangement was made for the manganese steel ingots produced at the Imperial works to be rolled into rails by the Workington Iron and Steel Co., a major producer of railway rails in Cumberland. The rails were returned to the Imperial works, where they were assembled into points and crossings. A new large foundry building was completed in 1913, increasing the demand for labour; over 500 people were now employed in the works.

William Edgar Allen died in 1915. He had been a beneficent donor to the city of Sheffield. His memory is perpetuated in the city by the endowment of the Edgar Allen Library building at the university, which was opened in 1909 by the future King George V and Queen Mary, and by the Edgar Allen Institute for Public Health.

The Park View Steel Works, which had been established for about 50 years, with tilt hammers and a forge, was acquired in 1915 to expand the capacity for fabrication of engineering tools and a 500 t press was installed at the Imperial works. Otherwise, few changes were made during the First World War. In common with most of the other steelmakers, significant developments were put in hand for when the war ended, in anticipation of a surge in demand for steel for civilian purposes. These included the installation of a 10 t electric arc furnace to replace the open hearth furnace for duplex operation, reducing the tap to tap time for the final refining stage to about 2 h. A new plant was built for the production of railway points and switch gear at Shepcote Lane, near to the Imperial works in Sheffield. The expected boom did not materialise, however, and the loss of export orders which resulted from the imposition of tariffs on imports by the USA and several European countries in the early 1920s created a recession with severe fluctuations in profitability.
Innovative developments were continued despite the financial problems. The third and perhaps the most significant development in steelmaking introduced by the company was the installation in 1927 of the first coreless high frequency induction furnace in the world for melting steel. This gradually replaced the crucible process for the manufacture of tool steels. Tool manufacture was now focused on appliances with a cutting edge and file manufacture was discontinued. Using the new melting facilities, tools were produced from 'Stag Major' high speed steel containing 21%W, and 12%Co, which could be used for machining manganese steel castings and forgings. 'Maxilvry' austenitic stainless steel was also introduced and new plant was installed for the production of magnets.

Up to this time, each high speed cutting tool had been shaped from one piece of metal. In 1929 the firm pioneered the production of composite tools, initially with high speed steel tips brazed on to carbon steel shanks, to reduce the cost. The brazed joint proved to be unsatisfactory in terms of strength and heat resistance so, two years later, butt welded tools were introduced under the 'Stag Major Superweld' trademark. The British Rema Manufacturing Co. Ltd, Halifax, was acquired in 1939 and the plant in use there for the manufacture of crushing and grinding machinery, disintegrators and air separators was transferred to Sheffield.

A shadow factory was opened at Denby during the Second World War to diversify the manufacture of Superweld tools. A new research department was also opened and the company experimented with the production of molybdenum containing high speed steels to circumvent the wartime shortages of tungsten. A new melting facility containing two acid lined Tropenas converters of 3.5 t capacity was completed in 1944 and a soda ash treatment was developed for the production of steels with a very low sulphur content. A radiographic laboratory housing a 400 kV X-ray set was completed shortly after the war ended. This was one of the earliest uses of radiography in Britain for the inspection of castings.

The acquisition of companies with related interests was resumed with the purchase in 1952 of the Buell Combustion Co. Ltd, London, manufacturers of dust collection and drying equipment, and the magnetic chuck maker, J. H. Humphreys and Sons Ltd, Oldham, in 1955. A new building for the production of engineers' tools was opened on the Shpocote Lane site in 1954. The production of tungsten carbide cutting tools by powder metallurgy techniques had been started by the company on a small scale in the late 1930s and in 1956 a large new plant was installed at Shpocote Lane for the manufacture of hard metal (Ta, Ti, W) alloy carbides. The new range of products included 'Stag Allenite' WC tipped tools for planing steel and 'Stag Athyweld' WC tipped tools made by a deposit welding procedure. A new heat treatment department was opened in the Imperial foundry in 1958, with a triple chamber heat treatment furnace capable of stress relieving castings up to 12 t in weight and with facilities for annealing, normalising, quenching and tempering.

At that time the melting facilities comprised two acid lined cupolas (120 cm internal diameter), two 4 t Heroult electric arc furnaces with basic linings, two 3.5 t acid lined Tropenas converters, and four high frequency induction furnaces rang-
ing from 50 to 500 kg capacity. The latter were used for the production of Alnico steel magnets and Nichrome alloys in addition to the production of high speed and corrosion resistant steels. Metal from the larger furnaces was processed into castings covering a wide size range and weighing from less than 1 kg to 14 t finished weight, with an output of about 150 t/week. A large volume of 12%Mn steel castings was produced for fabrication into railway and tramway track, but a diversity of other components was produced for assembly into appliances such as shot blasting equipment and high speed swing grinders. A 250 t press for straightening castings was installed in 1955.

A subsidiary company, Edgar Allen Noyes Pty Ltd, was opened in Australia in 1957 and became a wholly owned subsidiary in 1960. The Sheffield Hollow Drill Steel Co. was bought out in 1961 and Aerex Ltd, a Sheffield firm that manufactured axial and radial fans and fan installations, was purchased two years later. The range of tools was extended with the introduction of negative rake tool holders for use with throwaway sintered carbide tool tips.

The total steel output from the company was well below the threshold set for the compulsory purchase of the assets by the nationalisation act of 1967, but an internal reorganisation was implemented to reduce the risk of a later sequestration. From April 1967 the parent firm became a holding company and each of the manufacturing divisions was incorporated as a subsidiary company. At this time the company had about 2000 employees. The threat of state intervention rapidly receded, however, and British Steel Corp. eventually sold to Edgar Allen the tool and high speed steel factory at Openshaw which it had acquired with the nationalisation of English Steel Corp. An AOD furnace was installed to meet the increasingly stringent requirements for manganese steel and other high grade steel castings.

The large increase in the price of fuel oil in 1973 caused a severe recession in the industry and many of the smaller companies were unable to survive the financial crisis that followed. Edgar Allen was not immune from the crisis and in 1975 the company merged with Balfour and Darwins Ltd to form Edgar Allen Balfour Ltd. Balfours was founded in 1865 as a crucible steel works and tool manufacturer under the name of Siebohm and Dieckstahl. This name was changed during the First World War and Arthur Balfour became the major shareholder. The company was the first to produce high speed steel in this country, one year after the original patent was granted in the USA in 1900. Darwins had started in 1906 as Darwin and Milner Ltd, and had specialised in later years in the manufacture of razor blades. Both of these Sheffield companies were early users of induction melting, shortly after the process was introduced by Edgar Allen. They had merged in 1964 and their activities integrated well with the Edgar Allen tool division. Finance remained a problem for the new company and eventually, in 1979, it was bought out by Aurora Holdings Ltd, a shell company owned by a merchant banker, Sir Robert Atkinson, which also had bought out Osborn Steels Ltd in the previous year, to form one of the largest special steel manufacturers in Britain. A large increase in the bank interest rate almost immediately after the purchase was completed, however,
imposed crippling loan charges on the company. The Park View works was closed in 1980 and the Imperial works followed soon afterwards. When the Openshaw works was closed down in 1983, it brought to an end all steelmaking by the company. The company continues to make railtrack points and crossings and to manufacture sintered tools at Shepcote Lane.

ENGLISH STEEL CORP. LTD

by C. BODSWORTH

The English Steel Corp. was formed in 1929 by the merger of the steelmaking and allied interests of Cammell Laird Ltd with Vickers Armstrong Ltd. Both of these firms had also been created by amalgamations and had undergone a number of name changes in the process. They had a significant influence on the development of the iron and steel industry in and around Sheffield from the middle of the nineteenth century. A more detailed account of the background in which this development occurred has been provided by Barraclough and an outline of the formation and growth of the company has been written by Cookson. Some of the data in this section have been based on these publications.

Cammell Laird and Co. Ltd

This firm started in 1837 when Thomas Johnson and Charles Cammell formed a business with the name Johnson Cammell and Co. as file and steel manufacturers in a small workshop in Furnival Street in the centre of Sheffield. Steady growth in the demand for the products necessitated a move to a larger site and the Cyclops works, occupying 0.8 hectares, was opened in 1845. This was the third works to be built to the east of the city centre in the area that was to become the heart of the Sheffield industry. Within 10 years of the move the company was operating eight cementation furnaces to produce blister steel and crucible melting was soon added.

Thomas Johnson died in 1852 and 3 years later the name of the firm was changed to Charles Cammell and Co. In 1861 the Cyclops works was extended to accommodate a Bessemer converter plant and a rail mill. Puddling furnaces for the production of wrought iron and puddled steel were also built and the company began the production of iron armour plate. Two years later the first press in the world for forging steel was installed at the Cyclops works to make gun barrels and turbine shafts. This was used also in the first stage of shaping wrought iron armour plate.

The rapid growth in the demand for wrought iron and steel for railway construction led to the erection of the Grimesthorpe (Sheffield) plant between 1863 and 1865. This works initially developed the production of railway castings and tyre and axle forgings, but subsequently expanded into the manufacture of ordnance, heavy forgings and marine components. The firm became a limited liability
company in 1864 with an authorised capital of £1 million. In the same year a chemical analyst was appointed and the Yorkshire Iron and Steel Works at Penistone was bought out. This works was owned by Benson, Adamson and Garnett, who had installed Bessemer converters there and had patented a number of improvements to the converter process. It also operated cementation and crucible furnaces. A rail mill was now added.

A major export market for steel railway rails was developing in Europe and America; so in 1872 a new Bessemer works, the Wilson–Cammell Patent Wheel Co. with four converters, was erected at Dronfield, near Sheffield, and the rail rolling mills were transferred from the Cyclops works to the new plant. The site proved to be too remote, however, from the supplies of low phosphorus iron required for the acid Bessemer process and from the docks for rail exports, so the Derwent Iron works at Workington in West Cumberland was purchased in 1882. The equipment and most of the workforce at the Dronfield works were transferred to the Cumberland plant, where molten iron from the blast furnaces could be transferred directly to the converters and the rails could be shipped from the nearby port of Whitehaven. Six converters, each producing 500 t/week were dedicated to rail production. By 1895 two more Cumberland iron works had been purchased and the company was now operating eight blast furnaces and eight converters there. The demand for the export of rails dropped rapidly, however, towards the end of the century as rail production began in the USA and other European countries and the profitability of the Cumberland works declined. Eventually they were sold to the Workington Iron and Steel Co., which was formed in 1909.

A demand arose for a stronger armour and in 1876 the company patented a process for the production of compound plate (Wilson compound armour). This consisted of a wrought iron plate onto which was cast a layer of eutectoid steel, and the composite was forged and rolled to produce plates up to 250 mm thick. The firm was now rolling armour plates weighing up to 35 t. An export market for the supply of armour plate to Russia was developed over the next few years. The first all steel armour plate was made in 1888, in which year an 8000 t forging press was installed in the Grimesthorpe works. Within a decade the company was producing differentially quenched, carburised alloy armour plate, following a similar process of development to that at the neighbouring works of John Brown and Co. Ltd. Charles Cammell died in 1879 and he was succeeded by the Managing Director, George Wilson, who died 6 years later.

During the latter part of the nineteenth century the puddling process was gradually superseded by crucible melting at the Cyclops works and open hearth furnaces were installed at the Grimesthorpe works during the 1870s. By 1900 the company was operating four acid Bessemer converters at Penistone and six acid open hearth furnaces at the Grimesthorpe works, with an annual capacity of over 0.5 Mt. In the following year a file factory was opened at Odessa in Russia, but the venture was not profitable and was closed in 1905. One of the first metallurgical laboratories in Sheffield was opened at the works in 1902, under the direction of T. Middleton.

Armour plate and ship plate was one of the main products of the Company.
Since Charles Cammell was the son of a shipowner, it was perhaps a natural development that the company, which he had founded now sought a greater involvement in the construction of ships. Accordingly, in 1903 the company amalgamated with Laird Bros., who had opened a shipyard at Birkenhead in 1856, to form Cammell Laird and Co. Ltd. The capital was increased to £3.4 million. The armament operations of Mulliner Wigley (Coventry Ordnance) were also acquired jointly with the neighbouring firm, John Brown. Three years later the shares in this company was exchanged for a half share in the Gaven plant of the Fairfield Shipbuilding and Engineering Co. (The Coventry ordnance works was transferred to the English Electric Co. in 1918 and closed down a few years later.)

A plate mill, claimed to be the largest in the world, was installed in the Cyclops works for rolling armour plate in 1906. The works was fully occupied with the production of armaments during the First World War. Due to lack of space for expansion in the Sheffield works, output was increased by the construction of six open hearth furnaces and a cogging mill at the Penistone works.

The first electric arc furnace was installed in 1919 for the production of alloy steels and the Leeds Forge was acquired in 1923 to process these steels. The forging of large cylinders was developed, but the company had difficulty during the 1920s in finding sufficient orders to diversify from the production of armaments.

Vickers Armstrong and Co. Ltd

Edward Vickers began his career in the industry in 1829, when his father-in-law made him a partner in his firm of Naylor and Sanderson. This firm produced steel by the cementation process and was one of the first to adopt crucible melting at its Millsands, Sheffield, works which were built in 1805. The name was soon changed to Naylor Vickers and Co. Vickers pioneered the development of procedures for the casting of steel, using locally mined ganister to strengthen the sand mould, and by the 1850s there were ninety crucible melting holes to supply the casting shop. He became chairman of the company, retiring in 1856, and was succeeded by his son, Thomas Vickers, who patented a process for the production of cast steel wheels in 1862.

Construction of the River Don works in the east end of Sheffield to expand production was started in 1863 and the business was transferred from Millsands works to the new plant in the following year. This eventually became one of the largest crucible steelworks in the world, with about 340 crucible holes. A larger number had been planned, but, during construction a change was made to the new Siemens gas fired regenerative furnaces for crucible heating, which allowed more rapid melting of the crucible charge. There were no cementation furnaces for carburisation of the crucible charges, for they were prepared from cast iron and wrought iron turnings, a procedure patented by William Vickers. The production of bells, wheels, gears, pistons and other large castings and ingots was developed by the sequence casting of several hundred crucibles via a tundish. In 1869 a 25 t ingot was cast from over 600 crucibles.
The company name was changed again to Vickers Sons and Co. Ltd in 1867 with an authorised capital of £155,000 and a railway tyre rolling mill was commissioned at the River Don works. The production of forged marine engine shafts was also started, followed a few years later by the casting of ship propellers. The first chemical analyst was appointed in 1870. Additional land was purchased to expand the works in 1874 and a new rolling mill was installed. Open hearth furnaces were built in the 1880s to increase the production of steel. By that time the authorised capital had increased to £750,000.

The company began to produce steel armour plate in 1888, in competition with Cammells, and 2 years later the first gun barrel forging was produced. In 1897 the business of Maxim Nordenfelt Guns and Ammunition Co. and the Naval Construction and Armaments Co. of Barrow were acquired. The Maxim Gun Co. had been started by Maxim, Symon and Albert Vickers in 1884. The Nordenfelt works commenced operations 2 years later and merged with Maxims in 1888. The further merger with Vickers to form Vickers, Sons and Maxim Ltd created a company with all the facilities required to supply the parts, build and arm naval ships. The first submarine (HMS Holland) built by the company was launched in 1901. In the same year the company diversified initially in a more peaceful direction, but laying the foundation for a later development to become the major supplier of armoured vehicles, by the purchase of the Wolsey Motor Co.

By 1902 the capital of the company had increased to £5.2 million. In that year the company made 10,000 t of armour plate and the machine shops had to be extended to cope with the rate of production. A half share in the Glasgow steelmaking, armour plate and shipbuilding firm of William Beardmores was bought in 1902 and a controlling interest in the American Electric Boat Co. was purchased in 1903. Two years later an association was formed with two Italian shipbuilders and the Terri Steelworks to construct an arsenal at La Spezia. A new ordnance factory and shipyard were also under construction at Glasgow. In association with W. G. Armstrong and Firth Browns, a company was formed to build a new Spanish navy and arsenal at La Carraca in 1908. Two years later the Canadian Vickers Co., Montreal was formed to construct a shipyard in Canada. This subsidiary was subsequently sold off in 1927.

The company had for some time been producing a 2W–1C tool steel and the production of 18%W and 6%Mo high speed steels was started in the early years of the twentieth century. A small research department was opened and J. H. S. Dickenson, the chief metallurgist, initiated pioneering studies on creep and temper brittleness. Over the next two decades a wide range of low alloy steels was developed, primarily to improve the penetration resistance of armour plate and to improve the penetration power of shells. Crucible melts of ferritic stainless steel were produced in 1914, only 1 year after Brearley's pioneering work. A drop stamping department began production at the River Don works in 1910. In the previous year, a 2.5 t electric arc furnace was commissioned and in 1911 a new electric melting shop containing one 3 t and two 8 t furnaces was opened. Maxim retired in the same year and the company name was changed to Vickers Ltd.
A new gun shop was completed just before the start of the First World War, making the firm the largest armaments manufacturer in the British Empire. Vast quantities of armaments were produced during the war and the works expanded to cover 40 hectares. Towards the end of the war, the company became involved in the construction of tanks and other tracked vehicles. This interest was continued after the war and in the 1920s it bought one of its main competitors, Carden Lloyd, to secure its position as the sole manufacturer of armoured vehicles in Great Britain.

The decline in orders during the recession in the 1920s led to a merger with Armstrong Whitworth and Co. Ltd to form the Vickers Armstrong Co. Ltd in 1928. William Armstrong started to produce ordnance in 1856 and for a time managed a wrought iron gun factory for the Government at Elswick. The Elswick Ordnance and Engine Works were combined to form Sir W. G. Armstrong & Co. in 1864. In 1882 this company merged with the shipbuilders, Charles Mitchell & Co., and a steelworks was built at Newcastle. Joseph Whitworth started to manufacture engineering tools in 1833 and moved into the manufacture of armour plate in Manchester in 1860. The two companies were amalgamated in 1897. Following the merger, a large rolling mill for the production of armour plate was opened at Openshaw, Manchester. Whitehead and Co., who manufactured torpedoes at Weymouth, was acquired in a joint purchase with Vickers in 1906. The Openshaw works was extended in 1912 and the plant was in full production through the First World War, but the company had great difficulty in re-orienting the production when peace returned and staggered from one financial crisis to another throughout the 1920s. About half the nominal value of Vickers' capital of over £20 million was written off in 1925, but Armstrong Whitworth was in greater difficulty and the merger with Vickers was instigated by the Bank of England to avoid the company going into receivership.

Both Cammell Laird and Vickers were suffering from the dumping of cheap imports into Britain by foreign competitors. The total annual steel production from all their melting shops of about 30,000 t was only a little over half the actual capacity. The Government was applying pressure for rationalisation of the industry as a condition for the introduction of a tariff act. It was agreed accordingly that the two companies would combine their steelmaking and related interests from 1 January 1929. The engineering and shipbuilding activities were retained by the parent companies.

English Steel Corp. Ltd

Rationalisation of the works proceeded slowly at first but began to accelerate as the industry recovered from the recession. A major portion of the Cyclops works, the Penistone plant, the Whitworth Forge in Manchester and the forge at the Grimesthorpe works were closed down. Steel castings were now produced only at Grimesthorpe, while forging and armour plate production was located at the River Don works. A lot of the equipment was obsolete or worn out, however, so an
ambitious programme for re-equipment was authorised. A new open hearth melting shop with three 60 t open hearth furnaces was built in 1932 and a 7000 ton hydraulic press and drop stamping machines were installed at the River Don works. Two 10 t arc furnaces and induction melting replaced the last of the crucible furnaces. Research work was located at the River Don works where a staff of more than sixty under J. H. S. Dickenson did pioneering work in the development of creep resisting steels. The production of alloy steel billets, forgings and castings was steadily expanded. New equipment was installed in 1933 to increase the production of stainless steels, but the growth in demand was slower than expected and in the following year a new company, Firth Vickers Stainless Steels Ltd, was formed in partnership with Thomas Firth Ltd. Production and fabrication of stainless steel was now concentrated at Firth’s Tinsley plant and ceased at the River Don works.

The company was fully occupied with armaments production during the Second World War. A new electric melting shop with forges and rolling mills was built at the Openshaw works, Manchester. Darlington Forge had been bought by the company in 1931, but was closed down for several years thereafter. New melting furnaces and forges were now installed there for armament production. A 30 t arc furnace was commissioned at the River Don plant. Very little other equipment was added at the Sheffield works, but the output rose to about 400,000 t per annum and continued at a similar level after the war. This was well above the minimum production level set for nationalisation by the 1949 Act of Parliament and, accordingly, the shares of the company were acquired by the Government on the vesting day in February 1951. Three years later, the company was restored to private ownership, three-quarters of the shares being held by Vickers and the rest by Cammell Laird.

Very large castings and forgings were now being produced by the company. The Grimesthorpe works produced a casting for export to the USA weighing over 180 t, while the River Don works forged a boiler drum over 60 t in weight and over 12 m in length. Production was constrained by lack of space, so in 1954 a 200 hectare site was purchased at Tinsley Park to build a new works adjacent to the Shepcote Lane rolling mills which had been opened by Firth Vickers Stainless Steels Ltd. Work started on the construction of a large machine shop at the River Don works, which was completed in 1959, but construction at Tinsley Park was delayed until 1960. The new works, containing two 100 t arc furnaces, a DH vacuum degassing unit, bloom, billet and bar mills came into production in 1963. By the following year the total output from all the works was 525,000 ingot tonnes. It is ironic to reflect that if this additional output had been delayed for one more year the company would have continued as a private operator. But it exceeded the minimum output of 483,000 t in 1964 which was set as the criterion for re-nationalisation and the company was absorbed into the British Steel Corp. (BSC) in 1967.

In subsequent years, BSC concentrated its foundry and forging activities at the River Don works and this became the headquarters of the Sheffield Forgemasters Group in 1982. The Tinsley Park works continued in production for a time, but most of the plant had been demolished by the mid 1980s. The remainder was
absorbed into the Shepcote lane works which was then operated by Avesta Sheffield Stainless Steels. The Cyclops site was occupied by the armour and associated products division of Avesta.

THOMAS FIRTH AND JOHN BROWN LTD

by C. Bodsworth

This company was formed in 1930 by the merger of the steelmaking and related activities of two firms which occupied adjacent sites in the east end of Sheffield. The merger resulted from the depressed state of the steel trade in Britain at that time. The Government applied pressure for rationalisation and re-organisation as a condition for the imposition of tariffs to protect the industry from subsidised deliveries by overseas competitors, which were saturating the British market. In the early years the products of the two firms were more complementary than competitive except in one respect. Both were heavily involved in the production of armaments. Each time that Firths succeeded in increasing the penetrating power of the shells which they produced, Browns sought to nullify the effect by making stronger armour plate. In later years the company had a worldwide reputation for the invention and development of alloy and stainless steels. Details of the formation and development of the two companies have been produced and some of the data in this section are based on those publications.

John Brown & Co. Ltd

John Brown started his career as a travelling salesman of steel. In 1837 he purchased a small works in Furnival Street, Sheffield, to make steel files. The rapid development of the railways soon led to diversification into the production of laminated railway springs and in 1849 he patented the first conical spring buffer for use on railway carriages.

To allow room for expansion and increased production, the Queens Works on a 1.2 hectare site in Saville Street was purchased in 1856 and renamed the Atlas Steel and Spring Works. Tool steel was produced from forty crucible furnaces. Throughout the eighteenth century all the wrought iron used in Sheffield had been imported from Sweden, but the new works included twenty-four puddling furnaces for the production of this material. Over the next three years eight 35 t cementation furnaces were installed and two Nasmyth steam hammers, tilt hammers and rolling mills were erected to fabricate the metal.

Increasing sales soon exceeded the capacity of the works and an adjacent 4 hectare site was acquired in 1859. Ten more cementation furnaces, forty-eight puddling furnaces, crucible furnaces and a variety of rolling mills were built. A foundry was opened in which iron castings weighing of 50 t were made. The plant
was now capable of producing 24,000 t of iron and steel per year. Wrought iron plate was produced, initially for boilers and bridges, but, by 1860, this developed into the production of armour plate up to 100 mm in thickness. Three years later new plate mills were installed with rolls 2.5 m wide and 800 mm in diameter to produce sheets up to 300 mm thick and weighing up to 20 t. A 2000 t Whitworth press was built for bending armour plate.

Meanwhile, Henry Bessemer had opened a small steelworks adjacent to Brown's works in Sheffield, in which he had proved the ability of his converter to make an acceptable quality of steel, given the correct charge materials. Courageously, in the face of the poor reputation that the Bessemer process had acquired, John Brown took out a licence in 1860 and installed a 4 t capacity converter at the Atlas Works. The venture was successful and the steel was used initially for the manufacture of railway tyres, which were marketed at less than one-third of the price of the wrought iron equivalents. A start was soon made in the production of railway rails.

The Companies Act of 1862 allowed money to be raised by the issue of shares. John Brown took advantage of this act and the status was changed to a limited liability company in 1864. The capital raised by the share issue was used to finance an extension of the Bessemer plant, increasing the number of converters to six, and the installation of a new rail mill. Rails now formed about 75% of the output and the firm employed over 3000 people. But the gradual development of rail production in the countries where they were required and the distance of the works from a deep water port resulted in the progressive loss of this trade and the rail mill was closed down in 1874. A temporary decline in the demand for naval armour plate in the late 1860s, coupled with the decline in rail production, led to a diversification into the production of large steel forgings.

John Brown had received a knighthood and resigned in 1870 after disagreement with his fellow directors. He was succeeded by one of the partners, Mr J. D. Ellis. The company now set out to secure its raw material supplies. Two blast furnaces were erected at the Atlas Works, iron ore mines were acquired in Northamptonshire and in Spain, and two collieries were bought to meet the coal requirements. A third blast furnace was used for the production of ferromanganese. At the opposite end of the scale, in 1871 chromium steel was produced in crucible furnaces at the Atlas Works, the first made in Britain. A few years later the company started to produce ship plate, using the space released by the decline in rail production.

A Siemens open hearth furnace was installed in 1879 and the Bessemer converters were scrapped in the next decade, although a side blown Robert converter was installed to supply metal for the foundry. By 1900 five open hearth furnaces were in operation.

The increased penetrating power of shells produced by Firths led to endeavours to produce stronger armour and, in 1877, a patent was taken out on the name of Mr Ellis for the production of compound plate. This consisted of a wrought iron plate onto one surface of which a layer of steel was solidified and consolidated by rolling. By 1891 further improvements in the penetrating power of shells required the
development of even stronger armour and a patent was granted to the company for spray-quench hardening the surface layers of an all steel plate. In the following year a new (Harvey) process was adopted in which the plates were surface carburised before quenching. Then, in 1899, a licence was obtained for the differential quenching of a Ni–Cr armour plate. A new plate rolling mill was commissioned and ten heavy presses were installed over a number of years in a new press forging shop. One novel feature was a large hollow rolling mill which was erected in 1905 for the production of rings and tubes.

Plates had been supplied to shipbuilders for some years, but with the increase in the capacity for plate production the firm now diversified into shipbuilding. The Clydebank Engineering and Shipbuilding Co. (which was founded in 1846) was acquired in 1889 and a major interest was bought in the Belfast yard of Harland and Wolff in 1907. Many famous ships were built by the company over the next few decades, including the passenger liners Lusitania, Aquitania, Canberra, Windsor Castle, Empress of Britain, Queen Mary and Queen Elizabeth and the battleships HMS Barham, Hood and Repulse. The Lusitania was one of the first ships to be built with 1%Si steel plates to increase the toughness and decrease the weight.

Firth's works, adjacent to the Atlas works, was frequently involved in the production of forgings and turbine castings for the ships and other joint activities had been developed. Consequently, in 1903, John Brown & Co. Ltd purchased a controlling interest in Thomas Firth and Sons Ltd. At this time the capacity of the Atlas works had grown to reach about 100,000 t of iron and steel per year. A half share in the Coventry Ordnance Co. was bought in the following year, the other half share being held by the neighbouring Cammell Laird Co. The Trent Iron Works and more collieries were purchased in 1907 and the blast furnaces at the Atlas works were closed down in 1911.

An innovative development was the opening of the Brown Firth Research Laboratories in 1908, under the direction of Mr Harry Brearley. The laboratories were involved immediately in the development of new alloy steel compositions and treatments. Although most of the production of these steels was accommodated in the Norfolk works, the demand that arose during the First World War led to the installation of a new rolling mill and extensions to the forge in 1915, the first electric arc furnace at Atlas works in 1916, and a new hammer shop and a 2000 t forging press in the following year. The foundry was moved to Scunthorpe to allow more room on the site.

In expectation of a postwar boom in the demand for steel products, the machine shops were extended and new tyre rolling mills were erected. Shares were purchased also in the English Electric Co. and the Craven Railway and Carriage Co. But the boom did not materialise and the recession in the 1920s, as noted earlier, led eventually to the complete merger with Firths.

**Thomas Firth and Co. Ltd**

Thomas Firth and two of his sons built the Portobello Works on a small site in
Charlotte Street, Sheffield in 1842 with six crucible melting holes and equipment for tool production. Thomas Firth died in 1850 and was succeeded by his son, Mark, by which time the restricted site was proving inadequate for the required production. Accordingly, the Norfolk Works was opened in the following year in Saville Street adjacent to the site which was occupied a few years later by John Brown's new works. Cementation furnaces and eighty crucible melting holes were installed, together with bar and sheet rolling mills and tilt hammers to produce cutting tools and files from imported Swedish iron. A large part of the production was exported.

A forge was leased at Claywheel Lane in Sheffield and the first gun barrel was made there by the firm in 1852. The equipment soon became incapable of handling the increasing size of the ingots, so a new gun forge with large steam hammers and a range of smaller hammers was opened on a site adjacent to the Norfolk works in 1854. Further expansion followed in 1856 with the opening of the Whittington Works at Chesterfield with 18 puddling furnaces to produce iron and steel, together with a foundry, forge, rolling mills and machine shops to make ingot moulds and structural sections. A shot forge, equipped with two 25 t Nasmyth hammers were built at the Norfolk works in 1864 to expand the production of guns and projectiles. At the same time the file and tool shops were moved to a new site to allow expansion of the crucible melting shop, which progressively increased in size until it contained 360 melting holes.

The first inner gun barrel made from crucible steel was cast in 1860. Within a few years the company was producing a wide range of weapons, from barrels for Enfield rifles to rifled steel barrels for 12 t cannon. Multiple pouring of crucibles through a tundish into the mould was by now well established and the size of the castings increased as larger gun barrels were made. The history of the company\(^3\) records that 1000 crucibles (equivalent to four melts from each crucible hole then in use) were required to cast the inner and outer barrels of a 35 t gun in 1871. Five years later the company was producing barrels for guns weighing 100 t to fire projectiles that could penetrate the thickest wrought iron armour then produced. This led to the development of the compound armour plate by John Brown. The Firth works was now the principal manufacturer of ordnance for the British Government and had a strong export market for guns. A 2000 t press was installed for the production of the larger gun barrels and this was used also for the forging of marine engine shafts.

Mark Firth died in 1880 and was succeeded by his younger brother, Charles Henry Firth. In the following year the firm was incorporated as a limited liability company. The first metallurgical chemist was also appointed. Four years later the melting facilities were vastly increased by the erection of one 10 t and one 25 t open hearth furnaces. This allowed production to be concentrated at the Norfolk works and the Chesterfield plant was closed in 1887. The crucible process was continued for the production of tool steels and by 1890 the output of crucible steel exceeded 5000 t/year. Two more open hearth furnaces were built during the 1890s. These replaced the cementation furnaces and only three were left in use by the end of the century.
The Saville Street Foundry Co. was acquired in 1898 and converted into the East Gun Works to increase the production of ordnance. The penetrating power of the shells produced by the firm was continuing to rise. In 1886 a licence was obtained from a French company for the production of shells with chromium steel tips and, 4 years later, capped shells were being made which easily penetrated 100 mm thickness of hardened armour plate. Then, in 1900, the first shells were made with a bursting charge which exploded on impact.

Tool steels had been a major feature of the company's products throughout its existence. Tungsten high speed steels became available in 1900 and the company immediately took up the manufacture of this invention. The tool shop was extended in 1903, again in 1906, and trebled in size in 1913, producing engineers' tools and rock drills which were marketed under the trade name 'Speedicut'. To allow room for more expansion, the crucible melting shop was transferred to a new works in Weedon Street in 1907 and new hammers, rolling mills and heat treatment furnaces were installed for tool steel production. The output of tool steel increased from 100 t in 1902 (when the total production of all products was about 40,000 t) to 1000 t in 1916. The steel foundry was also vastly increased in size.

The company had developed a good export market, but trade was particularly strong with the USA and Russia. Moves were now made to consolidate these markets and evade import duties. In 1896 a merger was arranged between the firm's sales interests in the USA and the Wheeler Sterling Co., USA, to form the Firth Stirling Steel Co., Pittsburgh, PA, which produced crucible steel and artillery shells. A file factory was opened in 1901 at Riga in Russia and two years later the Salamander Works was purchased. An open hearth furnace and two crucible melting holes, rolling mills, presses and a foundry were installed. When the Russo-Japanese war started in 1904 this plant was engaged in the production of armour piercing shells. Harry Brearley was recruited as the works chemist and, in that capacity, he invented 'Sentinel' wax pyrometers for measuring the temperature of the metal in the heat treatment furnaces. One year later he was appointed works manager and remained in that capacity until he returned to Britain in 1908 to equip and direct the new Brown Firth Research Laboratories. The Salamander Works was abandoned in 1915 when the German army advanced rapidly into Russia.

Electric power was introduced into the works for rolling mill drives in 1907. Four years later a 2.5 t electric arc furnace was erected for the production of alloy steels. Increased demand during the First World War led to the addition of a 4 t and an 8 t arc furnace at the Norfolk works and two 8 t arc furnaces at the Tinsley works. A new acid open hearth melting shop containing two 40 t and one 60 t fixed furnaces and a 25 t tilting furnace was built in 1918. A 1000 and a 4000 t forging press were installed and the tool factory was extended again. When the war ended, a new company Firth Derihon Stampings Ltd, was formed to manage the production of precision drop forgings. This was located in the National Projectile Factory at Templeborough, Sheffield, which the company had built and operated for the Government during the war.

While seeking to improve the erosion resistance of gun barrels, Brearley formu-
lated a low carbon steel composition contained 13%Cr which was successfully produced in 1913 in the newly installed arc furnace. The steel was found not to be suitable for its intended purpose, but Brearley noted its high corrosion resistance. According to Brearley’s account, the firm was not interested in his proposal to develop the steel for cutlery applications and refused to patent the invention or to share the royalties with him. Consequently, other companies in Britain were soon producing steel of this composition. The first heats were made in the USA by the Firth Stirling Co. in 1915.

The conflict between Brearley and the company led to his resignation in 1915 and he was succeeded by Dr W. H. Hatfield. The development of the chromium steels for commercial applications was prohibited during the war and the steel was produced mainly for aeroengine values. When the war ended, the research was continued under Hatfield’s direction. An exchange of information on Firth’s martensitic stainless steel and Krupp’s austenitic stainless, coupled with a royalty agreement, cleared the way for work on the austenitic grades in the early 1920s. Very short thereafter, Hatfield defined the 18%Cr, 8%Ni austenitic stainless steel composition and the production of stainless sheet and strip was started. The company was now marketing these products under the trade name of ‘Firth Staybright’ stainless steel. The carbon content of the austenitic grades could not be reduced below about 0.15% with the technology then available, so the microstability was increased by the addition of titanium to form TiC and prevent the formation of chromium carbides during treatment. By 1927 a 12%Cr, 12%Ni grade, with improved ductility and completely non-magnetic, was being marketed as Deep Drawing Quality. A range of other alloy steels was developed in the laboratories for high temperature applications and where very high or very low co-efficients of thermal expansion was required. The company also pioneered the development of Nitralloy steels for nitride case hardening.

Dr Hatfield played a leading role in co-operative research for the industry. He was the first chairman of the Iron and Steel Institute committee on the Heterogeneity of Steel Ingots and the Corrosion committee. When the Iron and Steel Industrial Research Council (the forerunner of BISRA) was formed in 1929, he was appointed chairman of the council’s finance and programmes committee. His efforts were recognised by the award of the Bessemer medal.

Thomas Firth and John Brown Ltd

When the steelmaking activities of the two companies were merged in 1930, John Browns retained the Clydeside shipyard and the South Yorkshire collieries under separate ownership. The issued share capital was £1.56 million with almost all the shares held by John Browns. The total output in the first year of combined operation was approximately 40,000 t. The British steel industry was in a severely depressed state and the following two years before the passing of the tariff act were traumatic for the steelmakers. Funds were found, however, to install a 30 t arc furnace, the largest in Europe at that time, and a high frequency induction furnace to
facilitate the production of alloy steels. All the electric melting had been transferred to the Firth melting shop. The Firth steel foundry was closed to make room for the extension of the melting shop and the foundry work was transferred to the Scunthorpe plant.

As the order book recovered under the protection of tariffs, the open hearth melting shop in the Atlas works was reorganised to accommodate the production of ingots weighing up to 200 t. Stainless steel consumption was showing only slow growth. In 1934 the production of stainless steel by the company and by the English Steel Corp. was combined to form Firth Vickers Stainless Steels Ltd, which was located in Firth's Tinsley (Sheffield) works. Two years later, the company acquired the site of the old Cammell's Cyclops Works from English Steel Corp. and new bar rolling mills and heat treatment plant were erected on the site. The tool factory was transferred to new premises in 1934 and crucible melting was discontinued following the addition of a second high frequency furnace for tool steel production. The steelmaking capacity was further increased by the addition of an 80 t acid open hearth furnace and a third high frequency furnace in 1937 and a 30 t arc furnace in 1940. Otherwise, few changes occurred until the end of the Second World War apart from an expansion of the research department. By then the output had risen to about 130,000 t/year.

Reorganisation in the late 1940s included the formation of Firth Brown Tools Ltd as a separate company to manage tool production, which was transferred to new premises. Surform tools were launched as a new product. The West Shell Shop was modified for use as a light machine shop and the armour machine shops were converted into a heavy engineering department. A sixth arc furnace and another high frequency furnace increased the melting capacity and the open hearth melting shop was modified to facilitate the casting of larger ingots. A small cogging mill and additional forging presses were installed. Rolling mill rolls, which had been made at the Atlas works from the 1920s, now became a major product of the company.

The tonnage capacity of the works was below the threshold set for nationalisation in 1949 and the company escaped the takeover by the Government. When the industry was released from state ownership, the company acquired in 1955 the Glasgow based steelmaker, William Beardmore and Co. Ltd, which had been established in the late nineteenth century and produced castings, wheel and tyres. With the growing threat of the renationalisation of the industry the company structure was reformed in 1962. Thomas Firth and John Brown Ltd became the holding company and Firth Brown Ltd was formed to manage the Sheffield steelmaking and Scunthorpe foundry activities. This proved to be unnecessary, however, for the output was again less than the criterion that determined which companies were renationalised in 1967.

A significant part of the postwar production comprised large, open die forgings in carbon steel, but the demand for these items declined rapidly during the 1960s. Consequently the decision was made to phase out this activity and concentrate on the production of high quality alloy and stainless steel products. The steelmaking facilities were changed accordingly. The first vacuum arc remelting unit was
installed in 1961, a second one in 1964, and two more were added in the next decade. An experimental electroslag refining unit, built in 1962, was followed by a commercial melter in 1964. A ladle degassing and inert gas stirring plant was commissioned in 1963. The company was then operating five acid open hearth furnaces of 35–100 t capacity, producing about 100,000 t/year. Five arc furnaces ranging from 10 to 30 t capacity and three air induction furnaces produced a similar quantity of steel. The open hearth melting was phased out between 1966 and 1968 and two of the induction furnaces were also scrapped. A vacuum induction melting furnace, the largest in Western Europe with 12 t capacity was installed in 1969. A new Atlas melting shop containing a 60 t UHP arc furnace and an ASEA-SKF ladle treatment unit, capable of producing 100,000 t/year, was commissioned in 1973.

Shortly after the end of the Second World War, the Shepcote Lane stainless steel cold rolling mill had been built as a joint venture by Firth Vickers Stainless Steels Ltd and the United Steel Companies Ltd. On the renationalisation of the industry the Government had acquired the shares in the mill which had been owned by Vickers and United Steels. Now, in 1971, the company agreed to transfer its holdings in Firth Vickers Stainless Steels to BSC in exchange for a balancing payment of cash and the withdrawal of BSC from the production of closed die and alloy steel forgings under 75 t in weight.

In anticipation of a growth in alloy steel trade, the company had bought the ferrous works of Jessop-Saville Ltd, a neighbouring specialist steel manufacturer, in 1967, but the orders actually decreased. Faced with decreasing profitability the company accepted a takeover by the Manchester based firm of Richard Johnson and Nephew Ltd in 1973 and the name was changed to Johnson, Firth Brown Ltd. Production was now diversified to include the production of forgings in titanium and nickel based superalloys, aided by the installation of a four hammer GFM precision forging machine. The market for steel forgings and castings continued to decline, however, and in 1982 Johnson, Firth Brown merged its steelmaking interests with the BSC River Don works to form Sheffield Forgemasters Ltd. Steelmaking was terminated in the Firth Brown works in the following year and production was concentrated at the former English Steel works. The new company was jointly owned by BSC and Johnson Firth Brown, but was subjected to a management buyout in 1988. All that now remains of this pioneer company in the development of alloy steels is part of the front wall of the office block.

THE HADFIELDS COMPANY

BY R. PENN

How Robert Hadfield ever came to start the crucible steel company that bore his name is shrouded in the past, for his profession when he began his company was that of a local rate collector. When his son, Robert Abbot Hadfield (destined to
become famous and widely regarded as the Robert Hadfield) was four years old (1862), the company trademark was acquired and Hadfields steel products were exhibited at that year's Manchester exhibition. Ten years later, the first formal part of the company (Hadfields Steel Founders) was established on the Hecla site, located on Newhall Road in the district of Brightside, which was rapidly becoming the steel area of Sheffield. Three years later, Hadfields castings won a prize at the 1875 Leeds exhibition, the first public acknowledgement of the company's product quality, which remained a major aspect of all Hadfields products. This award (and the notice of quality it bestowed) was mentioned in Whites Trade Directory for the Sheffield area in 1876. Around this time, young Robert A. Hadfield (RAH) had built a small crucible furnace in the cellar of the family home and was experimenting with both fuels and alloys for steel. His notebooks of that time show a progressive approach to the subject and his note for the day he first melted steel is triumphant. Once he found out how to melt steel, he became interested in casting the molten metal into useful forms. Having succeeded at that task, his next interest was to add various alloying elements to his melt and determine what effects they had on the solid steel. This work was to have overwhelming effects on both his fortune and that of the company which he would soon head.

At this time his father's company enjoyed steady, if unspectacular, trading until the mid 1880s. By 1882, RAH's experimentation had produced profound results, for in this year he produced the first compositions for manganese steel (later to become world famous as 'Hadfields manganese steel', after its inventor), for which he patented two compositions in 1883. Manganese steel was no overnight success; RAH spent the next four years overcoming production problems, so that, when the steel was put into production, artifacts could be fabricated without difficulty.

In 1887, manganese steel went into production at the Hecla works and, from that moment on, the fortunes of Hadfields (the company) and Hadfield (the man) were secured. So thorough had been RAH's researches and development that manganese steel was utilised only for the articles for which it was most suitable. Besides rock crushing plant and earth moving equipment, manganese steel was cast into military projectiles (shells); within that first year Hadfields had gained national praise for its 'notable castings (mainly 9 inch shells)'.

Robert Hadfield, the founder, died in 1888 at the age of 53, and RAH took over the mantle of Chairman of the Board of Directors. His impact was immediately felt: the company was incorporated, changing its name to Hadfield Steel Foundry & Co. Ltd, at that time employing some 400 men. That same year (1888) Hadfields was rated as being the best organised and having the best techniques in Sheffield and being far superior to any equivalent US company. This model company began to prosper. It obtained, also in 1888, the first large contract for armour piercing projectiles from the British government, followed by a similar order from the French government.

RAH presented his seminal paper on manganese steels to an audience of metallurgists in Sheffield, in which he revealed his knowledge gleaned over years of patient research. Another group of steel alloys from the same series of his experi-
ments were beginning to come to the fore: the silicon steels. Their electrical properties had intrigued RAH, but their forming problems restrained their introduction. Within two years these problems, and the final problems with manganese steel, were overcome and 1890 was a year of spectacular growth in the fortunes of the Hadfield company. Between 1894 and 1914 the company's share capital rose from £135,750 to £700,000; concomitantly the workforce grew from 530 to 5980. East Hecla (the best known Hadfields site) was built in 1897 on a large greenfield site next to the existing Hecla works. At the turn of the century, Hadfields established its own research laboratories at East Hecla, with the avowed aim of creating new steels by scientific means. Also in 1900, the company had only two sources of profits: armaments and commercial business. Manganese steel was used to produce 'Era' rolled steel armour plate in 1904, and from 1907 to 1914 Hadfields produced over 50% of the British government's armour piercing shells (a product where the company was the acknowledged world leader). Hadfields also made 'conventional' shells, ordnance accounting for 20% of its turnover. Part of the superiority of the Hadfields shells came from the routine use (from 1913 onwards) of electric arc furnaces uniquely for scrap remelting.

In 1908 Robert A. Hadfield became Sir Robert (a title by which he was known through the company ever afterwards). In 1909 he began to reduce his attendances at the Sheffield works; however, though not always there in person, Sir Robert kept a tight hold of the company and a keen interest in its doings. (His attendances at the works did not increase again until 1938, when the company, once more, began wartime production.)

Just before the onset of the First World War, Hadfields changed its name to Hadfields Steel Founders and Engineering Co. Throughout the war the company expanded massively owing to the requirement for armaments. Manganese steel was used to make tanks, over 4 million steel helmets for the troops, 3.5 million armour piercing projectiles from 12 lb (5.5 kg) to 18 inch (460 mm) calibre, complete guns, 200 mm howitzers and 6 inch (150 mm) trench mortars. By the end of the war (1918), Hadfields was the largest special alloy steel producer in Britain and Sheffield's largest employer (over 15,000 people), the site covering more than 200 acres. Dividends, paid to shareholders, performed equally spectacularly, rising from 22.5% in 1914 to 25% in 1915 to 30% from 1915 to 1918, plus a special dividend of 200% in 1918. Despite wartime pressures, research and development continued, Hadfields forging its first steel rolls at East Hecla in 1915.

In 1917, Sir Robert received a baronetcy for his contributions to the war effort. Board membership, at the end of 1918, remained unchanged until 1938. In some ways this stability was an important source of strength as political intrigues were avoided (unlike in other companies, e.g. Vickers), but it removed dynamism, the overall situation only being saved by RAH's grip on the levers of company control.

After the pressures of wartime production, late 1918 found Sir Robert in a more reflective mood; a newly installed electric rolling mill (part of the wartime expansion planning) commissioned after the armistice was promptly described by him as 'a terrible waste of money as there is now so much idle plant'. Sir Robert also
approached the government for a subsidy to help convert his company back to civilian work. Included in this package were three roll hot rolling mills, the largest being a 28 inch (710 mm) blooming and finishing mill, the others being 11 inch (280 mm) and 14 inch (355 mm) sizes. This peace boom did not last long. Inflation spread rapidly, Hadfields did not fully reconvert to civilian work for some years, and with inflation came the first serious labour dispute, when the moulders held a three month strike in 1919. This dispute lost over 29,000 tons of steel from the annual production.

Hadfields had a grip on the car industry steel market, a market which accounted for a large tonnage of steel. Being unwilling to lose this market (and be faced with either finding a new market for his surplus steel or cutting back production), Sir Robert sought to intervene directly. He did so, in 1919, by buying an interest in Bean cars, so as to guarantee the market for his steel. Each Bean car took 20–25 cwt (1016–1270 kg) of Hadfields grade 55 steel for the chassis alone, plus more for other steel components. In the same light as the interest in Bean, Hadfields began to make and sell steel mining wagons. RAH, the entrepreneur, began to supply projectiles to the US military. To keep costs low he was forced to manufacture in the USA and so took over Penfield-Bucyrus to form Hadfield-Penfield, leaving Bucyrus (though part of Hadfields) to deal with its previously established markets. Ballistic tests showed the superiority of the Hadfields projectiles, these being capable of penetrating any American armour then in use. Consequently the company wanted as many orders as possible. Between 1920 and 1923, Penfields' 'other half' (Bucyrus) seemed to have exploited the situation to Hadfields' disfavour, having drained money away in an attempt to re-organise. Bucyrus left the Hadfield organisation in 1924, but the new year saw further problems arise with Hadfield-Penfield when its costs were too high, so the company ran at a loss. By then Hadfields were making manganese steel for 11c/lb (24.2c/kg) in Sheffield, but the best Hadfield-Penfield could reach was 13c/lb (28.6c/kg). In light of this costing, more projectiles were exported from Sheffield in an attempt to secure Hadfield-Penfield, but a year later the American government dismissed Hadfields' projectiles, despite their technical superiority, by demanding that all military projectiles be US company made. Hadfield-Penfield struggled on until 1927, finally closing having lost £545,000 and with debts of £282,881.

Meanwhile, back in Britain, Hadfields' research interests re-emerged and in 1921 it joined the Heterogeneity of Steel Ingots Committee (Committee 5) of the Iron and Steel Institute. Hadfields' interests in this committee's work was principally hairline cracking in ingots. During the duration of Committee 5's interests, Hadfields also joined the Alloy Steels Committee. In the course of 1923, a serious disappointment arose for Hadfields, as the Bean car company collapsed. This year also marked the end of 10 years of consistent, sustained growth for Hadfields; from 1913 to 1923 its market capitalisation had increased by 400% and turnover had risen from £1.5 million to £1.9 million. RAH caused the company to invest in the reformed Bean car company in 1924, and car advertisements of the time made some play on the fact that Hadfields steel was used for these cars. Beans offered a reason-
ably advanced specification, servo brakes on all four wheels, four speed gearboxes and a spare wheel, quite sophisticated for 1924. Bean’s cheapest car was a 2–3 seat, 14 hp tourer at £295, its most expensive an 18/50 hp Laundette at £650. Two years later (1926) Hadfields purchased a controlling interest in Bean Cars and Sir Robert put his name to the idea that it was Hadfields’ intent to build a successful car company with the same care and price it had for the steel company. To this end Hadfields bought a drop forging and stamping plant at Smethwick and a company in Tipton to machine castings and undertake care assembly, both in 1927. A series of axle breakages in Bean cars in 1928 caused consternation and led to the finding that all the steel used in Bean cars did not come from the UK. It was found that the axle steel came, in fact, from America and was described by RAH as ‘cheap and insufficient steel’. East Hecla welcomed the Prince of Wales in 1928 to open a new super rolling mill, meant to be used mainly for car steels. Hadfields’ financial interest in Beans was first reported to shareholders at the 42nd AGM (February 1930), presumably as Sir Robert now believed it was secure and a fait accompli. However, Beans liquidated in June 1931, only to re-emerge within months completed owned by Hadfields (at a cost of £213,000). In the subsequent re-organisation the Smethwick forge was retained, but the Tipton plant was closed for car production, although retained by Hadfields for iron founding. Car production continued until Beans was sold to Hadfields in 1936 in a somewhat strategic move (1935 had seen the beginning of national rearmament, so presumably Hadfields wished to concentrate its efforts on its principal market). Smethwick Drop Forgings was founded from Hadfields’ interests in the residual parts of the Bean empire.

A Commission on Profits Made by the Private Arms Trade first sat in 1934 and reported in 1939. It validated Hadfields approach and exonerated the company from profiteering, saying that its profits were ‘in line’ for this trade. This was a timely decision as, from 1935 to 1938, Hadfields increased munitions output by 500% in response to national rearmament. Throughout the 1930s armaments had accounted for 17% of Hadfields’ turnover (cf. about 10% at Firth Vickers). From June 1935 this rose dramatically. Earlier in 1935, at the 47th AGM, it had been reported that the post-First World War re-organisation had never been completed owing to the 1930 recession and thus the company faced the demands of national rearmament still organised, in part, for wartime production. This year, too, saw the acknowledgement that Hadfields, once so relevant to American steel specifications, was losing influence there. By 1938, on the eve of the Second World War, the statistics of the company were impressive: 220 acres of site, of which 64 acres were buildings, over 8000 employees, 250 furnaces, and 25 miles of railway track, with Hecla producing mainly munitions. For steelmaking, sixty open hearth furnaces (both acid and basic) were used, as were arc and high frequency furnaces (up to 2 tons) for alloy steelmaking. The forging division had twenty-eight ‘hammers’, both steam and pneumatic, up to 4 tons capacity, twenty-five forging presses, up to 2000 tons capacity and produced forgings up to 30 ft (9.1 m) long and up to 16 tons in weight. Hadfields’ range of steels made at this time was: ‘Era’ manganese steel; ‘Era HR’ heat resisting steels; ‘Era CR’ corrosion resisting steels; ‘Hecla’ and ‘Era’ ATV
advanced turbine steels’ high grade carbon and alloy steels; high speed tool and mining drill steels. Immediately before the Second World War began Hadfields paid a dividend of 20%. Growth continued apace throughout the war, although Sir Robert died in September 1940. Within Hadfields, the work was divided thus: Hecla made shells and projectiles (over 4.5 million during the course of the war), while East Hecla undertook forging, rolling, foundry and engineering aspects. Dividends were still paid during the war and were 15% from 1939 to 1943, then 7.5% in 1944–1945. Midway through the war (1943), the Heterogeneity of Steel Ingots Committee finally reported. Hadfields had joined this working committee in 1921 and, as its part of the work had sectioned ingots from 13 cwt (615 kg) to 172 tons in weight, of all types of steel and of all complexities. Parts of this work had led to Hadfields staff proposing different methods of inclusion counting and also helped to develop vacuum hydrogen analysis techniques. Many of the findings of Committee 5 still resonate to this day.

With peace in 1945 came problems of diversity and of the nineteenth century character of some parts of the works and product lines. William Orr & Partners were commissioned to undertake a thorough review of the company and its work and to produce a report on the future of Hadfields and ideas about the product lines the company should follow in peacetime. Before the complete report was published, it appeared that Hadfields should find some outlet for its engineering capabilities, and, to this end, in 1946 purchased Millspaugh and Associates, papermakers, to make its machines with Hadfields steel. This was the beginning of a long relationship between these two diverse companies. Hadfields paid dividends of 5% in 1946, then 12.5% in 1947. By 1948, the Orr report was published and being implemented. Hadfields began a long and expensive (and overdue) re-organisation, designed to ensure that the company remained capable of meeting all postwar demands. Machine shops were extended and a new precision foundry built, but Hadfields still had to search for a new product line. One product line was found in earthmoving, Hadfields becoming the sole UK licence holder to make Esco earth-moving equipment and spares. In the Research Laboratory, Hadfields had been working with boron steel for control rods for nuclear fission thermal reactors and in 1948 began to manufacture rods in virtually pure iron–2% boron alloys, which were forged and rolled into 2 inch (50 mm) rods. Hadfields’ dividends, paid that year, were 17.5%. This level of dividend was not maintained, however; only 5% was paid in 1949 and 12.5% in 1950.

Nationalisation, in 1951, brought into being the National Iron & Steel Board and Hadfields was nationalised in the first wave of companies. Notably, during the nationalised period, Hadfields began the ‘25’ association for employees having 25 years standing in the company, the reward for which was an electric clock. (By the time this scheme ended, in 1970, Hadfields had presented over 2000 clocks.) From 1951 to 1953, the Iron & Steel board paid remaining Hadfield shareholders 11.66%. In 1954 the annual report minuted the facts that the research laboratories had made strides forward in steels for turbine usages and for nuclear purposes. Production, meanwhile, had succeeded with many complex forgings for a variety of aircraft
applications. These comments seem to harbinger a good period. Indeed 1954–1955 were good years, with sales, production and the foundry achieving their goals well. Selected for special praise was the precision foundry, which had demonstrated (and put into commercial production) castings of 0.3 g weight (probably the smallest production steel castings in the world at that time).

Denationalisation came about with the change of Government. For Hadfields, the Extraordinary General Meeting of 15 July 1955 voted to offer shares, initially to the original shareholders, where possible. In the report for this meeting the Hadfields organisation was given under the headings of: Research, Hadfields Steel Ltd, Hadfields Forgings Ltd, Hadfields Foundry & Engineering Co. Ltd. Immediately after denationalisation, Hadfields repurchased Millspaugh & Associates, but this time only after a bitter and costly struggle. Life continued on at an even tenor until the winds of the 1959–1960 recession were felt in the company, when the works were hit hard, but Research was unaffected, the laboratory producing new, higher boron containing steels. So advanced were these steels that the 4.75%B alloy could be forged into tubular control rods of 1.5 inch (38 mm) outside diameter and 1.125 inch (28 mm) inside diameter. A castable 6%B alloy steel was also available, which meant that the company could supply control rods to all nuclear stations at home and abroad.

November 1960 saw the first major industrial dispute of the postwar era, when members of the TGWU struck, the strike lasting to well into the new year. Dividend predictions for the 73rd AGM in February were 'poor' and by April of that year this once proud company was forced to go to the banks for a bank loan of over £1 million. Before agreement, the banks wanted backing for Hadfields from the Wellman, Smith, Owen Engineering group and Barrow Barnsley Holdings. Rumours of a £2.5 million package were confirmed when the commitment was finalised on 26 May 1961. This financial commitment brought about a group reorganisation, when 66.6% of Millspaugh shares were sold to Escher Wyss (Zurich); thus, Millspaugh left the group. This reorganisation also brought the first Polyvac analytical facilities into the company, plus more new manufacturing equipment, in the form of an 800 ton press and a new heat treatment furnace.

During 1961, too, Hadfields also unveiled its latest developments in consumable electrode vacuum remelting for producing alloy steel ingots up to 20 tons weight and 30 inch (770 mm) in diameter. An early use made by Hadfields of alloy steel from this plant was for the manufacture of fully through hardened steel rolls for aluminium foil production. Vacuum steam degassing for ingot and castings production was announced at the same time (this produced steel nearly as good as the consumable electrode process and much cheaper). An agreement in the same year with Memco of the USA was concluded for the production of embossing machines in the UK and allowed the production of matched hardened steel embossing rolls to fulfil demand and, incidentally, a product line for the consumable electrode remelted stock. Cold formable steel for the automotive industry became a priority in 1962, and Hadfields made its own press to test steels, but one motor manufacturer heard of this facility and requested Hadfields to use its machine to produce
25,000 forgings on a 'cost+' basis. Such contracts were (and are) difficult to refuse. Hadfields complied, demonstrating the need for such presses, and promptly began manufacturing similar oil/hydraulic presses in sizes from 150 to 2000 tons capacity as production items. In the 1962 annual report, it was stated that the demand for nuclear steels was increasing and that Hadfields' share of this market had increased. Consumable electrode re-melting and stream degassing were both in use for the ATV turbine alloys. By this time, the Hadfields group was: Hadfields Ltd (parent company) with Hadfields Steels Ltd, Hadfields Forging Ltd, Hadfields Foundry and Engineering Co. Ltd, The Manganese Steel Co., T. W. Johnson & Co., Cottam Stainless Ltd and Ernest Newhall & Co. as subsidiary companies in the UK; overseas subsidiaries were: Hadfields SA (Pty) Ltd and Hadfields Canada (1962) Ltd. Millspaugh was still there, being classified as an associated company. New members of the Hadfields group had been acquired for specific purposes: T. W. Johnsons to ensure special steels supplies, Cottam as stockholders to offer quicker delivery, and Ernest Newhall as a 'buffer' to keep steel supplies constant over time. A castings division was to be created from Hadfields Foundry and Engineering Co. and the precision and shell mould foundries would later appear in the 1963 annual report.

From 1962 to 1964, the Hadfields group made strenuous efforts to expand its trade with Eastern Europe, but without noticeable success, so in 1964 it installed £300,000 worth of plant, which represented the latest technology in both steel forging and casting. As a group, Hadfields enlarged once more in 1966, taking in two other companies; Eatad, immediately being taken onto the Hecla site (to supply pipe flanges for the oil and similar industries), and Tollemache Composting Systems Ltd (manufacturers of a vertical shaft ballistic pulveriser, to give an alternative method of dealing with domestic refuse). This was the Hadfield group as reported to the 79th AGM in February 1967. Within six months, however, this cosy image was overturned. In August 1967 Hadfields split to allow one part to merge with another company. The unit separated from the group was Hadfields Foundry and Engineering Co. Ltd, which merged with Samuel Osborn Foundry and Engineering Co. Ltd to form Osborn-Hadfields Steel Founders, a unit of the Osborn group. In many ways, both foundries were synergic, having similar products and licence portfolios, and, therefore, natural partners. Although this new company merged onto part of the East Hecla site, it was independent of the remaining units of Hadfields, but the new company was rapidly overwhelmed by cost and organisation problems. Many of these stemmed from the transitional arrangements where both sites operated simultaneously, accumulating losses of £0.9 million in 22 months of operation. By June 1969, the Osborn group could no longer sustain these losses and sold out to the Weir group, who bought it as part of its steel founding interests, renamed it O-HSF Ltd, and continued to operate from the East Hecla site. 1967 also saw the remaining parts of the Hadfields group announce the first compulsory redundancies, this period to be spread over one year. Later that year Hadfields announced a 'world first' in using oxygas injections directly into arc furnaces. Some months later that statement was coupled with an announcement that
Hadfields was spending £750,000 on a new 60 ton arc furnace for the East Hecla site, where this new technology would be utilised to improve quality and the production cycle.

Hadfields' independence came crashing down on 1 May 1968 when the remainder of the group was bought out by Dunford & Elliots for £4.7 million; this came out at 15 shillings (75p) per pound of book value. (With Dunford & Elliots came the Huntsman Co., the founding company of the Sheffield Steel industry). This takeover was backed by the unions later that year, thus ensuring, at least, an orderly transition, although the official Hadfields report called '1968 a momentous, but disturbing, year in which the loss of an important crusher order was unfortunate and [in] that the whole works were cloaked in an air of uncertainty'. Hadfields continued to trade as Hadfields (although widely, but unofficially, referred to as Dunford-Hadfields) until the Extraordinary General Meeting of 18 April 1978 sanctioned the name change to Dunford-Hadfields.

Death was formalised at the 91st and last AGM (28 February 1979), when closure was agreed. At this time the company and the whole industry were riven with strikes. East Hecla, that site so redolent of Hadfields, ceased trading in 1982, finally closed for the last time in 1983, only to be allowed to fall into serious disrepair before being demolished to make way for the Meadowhall Shopping Centre. Few people know, or care for that matter, that the bronze sculpture on the ground floor in the Meadowhall centre, representing three Sheffield steelmen pouring crucible steel into a mould, stands on the site from which one of the premier steel companies of Britain once traded.

The author spent some time 'on site' at Hadfields as an apprentice, and has pondered why what had obviously been a great company ultimately failed. His impressions are that when Sir Robert died a vital spark was extinguished, but the final spark was only quenched with nationalisation/denationalisation and that after that period Hadfields seemed to lose its way. That RAH relied too much on one product line (manganese steel in all its forms) is probably true, he notes. Having silicon steel to his credit and seemingly not exploiting it remains a mystery. Also, RAH's attempts to find a market for steel in the automobile industry were laudable, but taken, in hindsight, too far.

**SAMUEL OSBORN & CO. LTD**

**BY R. FENN**

Samuel Osborn was not the rapacious capitalist of the Georgian/Victorian era that one may think. A committed Christian and paternalistic figure to his workforce, his beliefs and actions suffused the whole of his business dealings and had a clearly discernible impact on the Osborn group even into the 1970s.
Osborn began his professional career by being apprenticed into the drapery trade in 1841 at the age of 15 to T. B. & W. Cockaynes, then to Thomas Ellis and Son (also drapers). Before he was ‘out of his time’ he moved, once more to Henry Rossall & Co. (a steelmaker). At the age of twenty-five he established a file and rasp making company in Brookhill (Sheffield) in 1851, which he formalised as Samuel Osborn File and Rasp Co. in 1852, with his stated business premises at 184 Brookhill, Sheffield. Despite national trading difficulties and the depression in manufacturing industries, in 1856 Osborn rented a six hole crucible furnace at 57 Carver Street (Sheffield) to make his own steel for his file and rasp company. In the same year, he also established a furnace facility in Plum Street, Pea Croft, in a part of Sheffield called Philadelphia. This furnace was to increase the output of steel to allow for some increase in manufacturing.

Another strand to the saga began in 1857, with Robert Forrester Mushett, who held the patent on adding spiegeleisen (ferromanganese) to the blown melt to deoxidise the bath, an idea that made the Bessemer process really viable. Mushett and the company for which he worked let the patent lapse because of the apparent lack of commercial interest in it. Once the patent had lapsed, however, Henry Bessemer utilised the idea without paying royalties. Mushett was responsible for producing the first steel railway lines and laying them in Derby railway station, where they operated without problems for many years.

During 1862 Samuel Osborn bought the Wicker site from Shortridge, Howell, and Co., naming it the Clyde Steel Works, and simultaneously acquired the ‘hand and heart’ trademark from Thos Ward (a pocket and penknife manufacturer), who first registered it in 1831. On the Clyde site, Osborn began and continued with steel refining which marked the start of the rise to international prominence. Clyde Steel Works, at this time, had twelve crucible furnaces and steam driven rod and sheet mills. Care for his workers’ health and a desire to alleviate the terrible conditions then predominating in British industry caused Samuel Osborn to change the file grinding bed (1863). (Another aspect of Samuel Osborns’ paternalistic approach to his workers occurred in 1871 when he was personally involved in the first workers Further Education College to be opened in Sheffield.) In 1864 he went on to patent the first machine for cutting files automatically. Financial success followed, such that on 1 January 1867 Samuel Osborn & Co. was founded and provided all of the steel for the first steamship built in China that year.

Robert Musheett made the first self-hardening steel in 1868 and exploited this as the first tool steel. In 1869 he added chromium to the alloy and sold this as the first ‘high speed steel’. Mushett was not the businessman that Osborn was, for in 1870 Mushett’s Titanic Iron and Steel Co. was wound up, but the company was taken up by Samuel Osborn & Co. From this time onwards, the fortunes and products of Osborn and Mushett became inextricably linked, with all Mushett’s processes and steels henceforward being produced at the Clyde Steel Works.

Disaster struck in April 1874, when the company had to suspend payments to creditors at 12s/£ (60%). Brookhill file workers took a 5% pay reduction for two years to help the company over the difficult period. In June 1875 Samuel Osborn &
Co. was liquidated, to the distress and grief of Samuel Osborn; however, in July the company was refloated with four partners, all of whom were ex-employees. In the November 1876 issue of the British Architect and Engineer Osborns’ new works (Clyde) were reported to have melting and casting facilities enough to produce steel castings, with steam hammers, two sheet mills, four rod mills, powerful shears, all powered by eight boilers and eleven steam engines. By 1878 Mushett’s ‘RMS’ self-hardening tool steel was described as ‘thoroughly established, the best and most economic[al] tool steel’. Business prospered and in 1882 all Clyde Steel Works employees were entertained at the Cutlers’ Hall in Sheffield to thank them for their loyal support throughout the difficult financial times. Samuel Osborn’s personal business ethics were demonstrated in February 1884 when all the creditors in the old, failed company were repaid in full.

The Rutland Road site was purchased from W. Butcher and Co. in 1885 and was the first foundry of its kind in Sheffield for commercial steel castings. It replaced the old Plum Street premises, but was much larger than the old site. Within the Rutland Road site, the smaller, virtually self-contained foundry was always called ‘The Philadelphia foundry’. Rutland Road foundry melting shop consisted of two Siemens acid furnaces, one of 2 tons (2220 kg) capacity, the other of 10 tons (11,100 kg) capacity.

Samuel Osborn died in 1892, leaving behind a solidly based group of companies. His ethos (workers’ health, workers’ education, commercial honesty) were well founded in the group and survived for as long as the group itself did.

Further developments in high speed steel occurred in 1909 when ‘Extra Double Mushett’ and ‘Triple Mushett’ tool steels were produced. This era, pre-First World War, was one of rapid growth and consolidation and laid a sound basis for munitions manufacture in the forthcoming war. In February 1910, Samuel Osborn & Co. purchased an interest in another Sheffield steelmaker, George Turton, Platts & Co. and then, in 1911 began producing tramway track in a new, dedicated company (Titan Tramway Track Co. Ltd). Steady growth continued, until in 1915 Clyde Steel Works was equipped with a Heroult electric furnace. In September of the same year Osborns purchased the Regent works site from Bury & Co. for rolling steel squares for personal and aeroplane armour, for guns and tanks (this required extension to existing premises and occurred at the Rutland Road side). Allied operations on the Belgian/French border caused the demand for light railway track to exceed supply. This led directly to an expansion of the Titan Tramway Track Co. production facilities to satisfy demand. Throughout the First World War, there was continuous expansion of Osborns’ foundry interests. Much of this expansion was to produce castings for armaments and ‘aerial’ bombs up to 5 cwt (255 kg) in weight.

Immediately after the end of the war (in 1919), Samuel Osborn & Co. returned to its paternalistic roots and were involved in workers’ education once more. On 30 August, the Osborn-Doncaster Day Continuation Centre school was founded for company apprentices. As an integral part of their apprenticeship, they were obliged to attend this college. More generally, the national working week reduced from 54 to 47 hours, while the group found it easy to get private funds for expan-
sion as calls for funds were rapidly oversubscribed. In this interwar period the fortunes of the group seemed to have reached their zenith with notable products or memorable events occurring almost every year. This is particularly noticeable from 1921 onwards when 'Rustless Plastic Steel', ST chisel steel and 'Tropic' hot die steel were all introduced. In 1925 Osborns' introduced a 'Hardening Service' for customers to come to the factory and learn how to heat treat their own 'RMS' steel tools. At the time of the General Strike (1926), S. O. & Co. workers thanked the company for the efforts shown to keep it going during 'these strenuous times'. A new cutting alloy ('SOBV') was introduced to the market in 1928 to machine manganese steel components. 'Solidend' tools (an 'SOBV' tool steel end butt welded onto a high tensile steel shaft) were introduced in 1930. Osborns was the first company to make and commercially market these types of tools. High frequency (HF) melting was introduced into the lower yard of Clyde Steel Works in 1931, and this was the first time that switchover gear was employed to allow two furnaces bodies to be run from one generator. During 1934–1935 the number of HF furnaces in use throughout the group was increased. A better tool steel 'Super Mushett 723' (a development of 'RMS' high speed steel) was introduced in 1935. In 1938-1939 a new series of tools specifically aimed at the armaments industry in response to the perceived war threat was introduced.

In 1939 Osborns began to position itself for work during the Second World War. To this end, a 24 inch mill to roll steel sheet was installed in the Regent works. The company became the largest producer of light gauge armour steel in the UK throughout the war years. 1940 saw a great expansion to cope with wartime demands. A 6 ton (6660 kg) Herault furnace was installed at Rutland Works, which led to an enlargement in the fettling and heat treatment departments. The large Rutland foundry was devoted to casting bomb casings, although manganese steel crusher components were also high priority jobs. During 1941 a small foundry (Holbrook Foundry, later to become Osborn Precision Castings) was established and dedicated to tank track production. Regent works was rolling aircraft steels for aircraft armour and engine rings. Low Moor Alloy Steel Co. was associated with the group and specialised in alloy steel extrusions. A new company for small engineers tools was opened in 1943; this was the Osborn-Mushett Tool works on Bacon Island (near the Rutland foundry). Mushett works made twist drills and small engineer tools from Osborn produced steels. Twist drill requirement rose by over 500% when compared with the requirement of the last year of peace. Mushett tools could no longer meet the requirement for tools when the heat treatment was performed 'out of house'; thus, in 1944 a new hardening shop for Mushett Tool works was opened. During the war years Osborns' contributions were not only to be seen on the munitions front; it also made as many of its scientists and engineers available to the government as were required. These people served on committees etc. to solve machining problems of all kinds. Between 1940 and 1945 group employee numbers rose to 3000, although these reduced to 2500 by the end of the war.

With the onset of peace came a time of re-organisation for the whole group, which occurred in 1947–1948 when subsidiary companies were formed. It was
(generally) within this final form that the Osborn group came to grief in the early 1980s. Group units and products were: Osborn Foundry and Engineering Co. Ltd (steel casting); Titanic steels (Mushett type and tool steels); Osborn-Mushett tools (drills and engineers tools); Bury & Co., a return to the original 1915 name (rolled steel); and Samuel Osborn & Co., which remained as the parent company.

In July 1948 Osborns launched its apprenticeship scheme. (The attitude to formal academic training followed the tenets of that instituted by Samuel Osborn himself and remained the fundamental aspect of Osborn group apprenticeships until the end.)

During the export drive of the 1950s Osborns took control of Low Moor in 1952 and concluded a licensing agreement with the Ohio Steel Foundry to produce Ohio designed steel castings to American railway standards; by 1959 the 'Ohio' castings range extended to oil refinery fittings. More American licences were obtained for castings at the end of the 1950s and on into the early 1960s. Among the most lucrative were the ESCO (Electric Steel Co.) earth moving components.

The rolling mill at Bury's had a large vertical furnace installed in 1959 for heat treating stainless steels. In that year, too, a licensing agreement was signed for exclusive use of the Shaw precision casting process. This process was installed at the Osborn Precision Castings site, where it was known as the Osborn-Shaw process. Much of the production of this process was in high alloy small castings (1 lb max. (<0.5 kg)). Shell moulding trials began at Holbrook, also in 1959. Files and rasps were still made (albeit in the Mushett Tool Co.) and still appeared in the group catalogue. This represented a continuous production span of 108 years. Manufacture of 'Caterpillar' track links for armoured personnel carriers (APCs) and light tanks had become something of a speciality during the war and remained so for years afterwards. In 1960, major orders for track links for the Trojan APC were gained and were intended for Osborn Precision Castings. The orders proved too large for Holbrook alone and so some were subcontracted to the Philadelphia foundry, where a shell moulding unit and casting lines were installed. In 1964 Philadelphia foundry (essentially part of the larger Rutland Road works) made the new, lightweight track links for the 'Scorpion' APC. Philadelphia foundry was reorganised to accommodate a shell moulding section to produce the overflow of the track link contract from Holbrook Precision Foundry. APC track links became, increasingly, the mainstay of the Philadelphia founding operation. To supply the burgeoning market for aerospace and high cleanliness steels, an electroslag remelting facility was installed at the Holbrook site in 1965, the intention of this equipment being to refine aircraft quality steels to supply to Low Moor extrusions.

Having not been included in the first stage of steel nationalisation, Samuel Osborn & Co. began tactical re-organisations in 1967 to enter in Stage 2 (proposed for about 1968). This was initiated by Osborns and involved, as a first step, all of its founding interests. Osborn Foundry and Engineering Co. merged with the foundry interests of Hadfields to form Osborn-Hadfields Steel Founders Ltd (on 31 July 1967). This new company was based on one-third of Hadfields' East Hecla site, although the new company still remained as part of the overall Osborn group.
Holbrook works became Osborn–Hadfields Precision Steel Castings, part of the new foundry group, but did not change site. This move led to the closure of the Rutland Road site in early 1968. Stage 2 nationalisation never happened and the Osborn group was left with the larger, overstated Osborn–Hadfields, with little increase in production to pay the bills. Osborn–Hadfields was an experiment that failed and in its failure rapidly bled the groups’ financial security away. By 1969 the foundry group had run the Osborn group close to bankruptcy. The foundry operations were brought by the Weir group (on 29 August) whereupon Osborn–Hadfields became O–HSF Ltd and, after 84 years, Osborns no longer had a steel foundry. Weirs closed O–HSF in the early 1980s after the long engineering strike of 1980.

The Osborn group never recovered from the double blow of the engineers’ strike and the bargain price paid for Osborn–Hadfields; their reserves were diminished, and although they could now concentrate on small and engineers tools, their fortunes were never to recover.

Innovation in cutting tools continued within the residual Osborn group. In 1979 Osborn–Mushett Tools patented a coddle drill (for CNC machines), but never reaped the rewards of this work. Aurora Ltd purchased the remnants of the effectively defunct Samuel Osborn & Co. Ltd later in 1979. Under the new management some site/company names changed (e.g. Low Moor Alloys became Osborn Steel Extrusions), others remained the same (e.g. Osborn–Mushett), some closed (e.g. Clyde Steel Works). The Clyde works closed between 1981 and 1982 and the company was liquidated on 27 November 1987. The years 1982–1983 saw the Rutland Road and Burys sites demolished and cleared, the old buildings being replaced with multipurpose buildings for light engineering companies. The Clyde Steel Works site was demolished at the same time and re-developed into office suites. In 1989 Aurora sold Osborn–Mushett to the Allied Newspapers Group (Fisher Karpark Holdings Ltd) because of losses incurred by delivery problems with Aurora high speed steel supplies to the tool works. Three years later, in 1991 Osborn–Mushett Tools Co. was taken over by F. K. I. Clarksons’ to become Clarkson–Osborn. With this re-naming, two famous names in the history of Sheffield steel (i.e. Mushett and Titan) disappeared. Clarkson–Osborn still operates from the 1943 Mushett tool works premises, the last surviving building of the defunct Samuel Osborn group. 1991 was also the year that Samuel Osborn & Co. Ltd changed its name to Aurora Group Ltd, the final curtain fall of the Osborn story.

The history of the Samuel Osborn group is really from 1852 to 1980. Famous names were associated with this group (Osborn, Mushett, Titan, etc.), but by 1991 none of the sites, except the Tool Works, existed. By then, most of the special Osborn culture and names were long gone, too. Samuel Osborns, once a proud and historic name in the annals of the Sheffield steel industry had effectively passed into the dust of time, leaving virtually no mark of its passing.
RICHARD THOMAS AND BALDWINS LTD

BY C. BODSWORTH

The company was formed in 1945 by the merger of Richard Thomas and Co. Ltd with Baldwins Ltd. The origins of both firms can be traced back to the middle years of the nineteenth century, but they were formed by the acquisition of and merger with many smaller companies, some of which had started to produce tinplate early in the eighteenth century. The original location of the British tinplate industry in South Wales and in neighbouring counties is often described as a happy marriage of Welsh iron and coal reserves with Cornish tin, aided by the proximity of the Welsh ports. Numerous pack rolling mills were established to produce the thin sheet gauges required for tinplate manufacture and the industry was fragmented into a large number of small works. By continued acquisition of their competitors, Richard Thomas and Baldwins eventually dominated the British output of tinplate and other coated steels. The wrought iron sheet, which was used when the two firms started in business, had been entirely replaced with steel by 1880, so both companies expanded at an early stage to produce their own steel supplies.

Richard Thomas and Co. Ltd

Richard Thomas leased the Lydbrook and Lydney tinplate works in Gloucestershire to form his own company, Richard Thomas and Sons, in 1875. Re-named Richard Thomas and Co. Ltd, it became a public company in 1884 with a capital of £50,000. Four years later, the Melingriffiths tinplate mills at Whitchurch were bought out. Over half of the tinplate produced in the UK was then exported to the USA, but this market was lost when the McKinley Tariff Act came into force in 1891 to protect the fledgling industry in America. Faced with a loss of market, many of the small tinplate mills were in financial difficulties. To increase market share, Richard Thomas bought out several of the mills in the 1890s, including the Bury Tinplate and the South Wales Steel and Tinplate Companies at Llanelly, South Wales Tinplate at Swansea, and Abercarn Tinplate at Newport. By the turn of the century the company owned about fifty mills. This had increased to seventy at the end of the next decade with construction of new plant at the Bury works and at the Richard Thomas tinplate works, both at Llanelly.

Frank Thomas, one of the sons of Richard Thomas, had acquired a significant footing in the tinplate trade through the purchase in 1896 of the Cwmfelin Steel and Tinplate Co., which he amalgamated with other mills to form the Swansea Tinplate Co. in 1901. Six years later he bought the Redbourn Hill Iron and Coal Co. at Scunthorpe, which had been founded in 1872 by Monks Hall. Over the next decade the Scunthorpe works was modernised and expanded. The number of blast furnaces was increased from two to four, smelting ore from the company's own ore
mines, and four 50 t open hearth furnaces and rolling mills were added during the First World War.

In 1918, following the death of Richard Thomas, Frank Thomas amalgamated his company with the family firm to become the largest manufacturer of tinplate in Europe. Five years later the Company bought out its largest competitor, Grovesend Steel and Tinplate Co., to achieve a dominant position in the industry, with about 200 tinplate and sheet rolling mills under its control. The Grovesend company had bought out six tinplate works, mainly in the Swansea area, shortly after the end of the war. Richard Thomas and Co. had also acquired some of the smaller operators. Orders for tinplate were scarce and each works was allocated a quota for tinplate production from a central pool. Several of the older works which were acquired were closed down, therefore, to increase the allocation to the remaining works within the group. The South Wales Tinplate Corp. was formed to market the products from the firm and from most of the remaining independent tinplate producers.

The depression towards the end of the 1920s caused severe difficulties for the company and the Redbourn works, which had been operated at a loss for several years, was closed in 1930. The tariff act and other Government measures to protect the industry restored confidence and the works was re-opened in 1932. An agreement with the Whitehead Iron and Steel Co. of Newport secured the transfer from Tredegar to Redbourn of that company’s semi-continuous bar mills, which were then operated as the Whitehead Thomas Bar and Strip Co. Ltd.

More tinplate and strip mills were bought out in the 1930s, but the most significant purchase at that time was the Ebbw Vale Steel, Iron and Coal Co. The objective of this purchase was to secure a site for the construction of a continuous wide strip mill, capable of producing 50,000 tons of coiled strip per annum at a finishing speed of 560 m min⁻¹. The Ebbw Vale works was founded in 1786 and was operating three blast furnaces by 1830. The works became bankrupt and was acquired by the Darby family of Coalbrookdale fame in 1844. By the 1850s it was operating blast furnaces fitted with a single bell to restrict gas discharge. It was one of the first works in the UK to install Bessemer converters for the production of railway rails and Mushet’s early trials to deoxidise Bessemer metal with ferromanganese were sponsored by the works in 1856-1857. A variety of schemes was formulated by the works in an attempt to circumvent the Bessemer patents, including an unsuccessful effort to refine molten pig iron by blowing air downwards onto the bath, the forerunner of the LD converter process. Eventually the company conceded the payment of royalties to Bessemer. The works was bought out by the Ebbw Vale Steel, Iron and Coal Co. in 1868. Two new blast furnaces were commissioned in the early 1920s, but the company was unable to survive through the recession and the works was closed down in 1929. When Richard Thomas and Co. acquired the plant the two blast furnaces were modernised, but the remainder of the works was obsolete and was demolished. New coke ovens and byproduct plant were built. Following the successful re-introduction of the basic Bessemer process by Stewarts and Lloyds Ltd at its new Corby works, it was decided to use the process again at Ebbw Vale. Accordingly, three 25 t converters were installed together with three 75 t open
hearth furnaces and an inactive mixer. The first continuous hot strip mill (1.4 m) in the UK was constructed on the site by the American Rolling Mill Co. (Armco) to feed two cold rolling mills and tinning lines. The purchase of the works included the Irthlingborough iron ore mines and a number of local collieries, so the company was self-sufficient for most of its raw materials.

Costs escalated rapidly during construction of the Ebbw Vale plant and a loan of £5 million had to be raised to complete the project. This was roughly equal to three-quarters of the total capital of the company at that time. The loan was raised by the Bank of England, with the condition that the Chairman of the Bank and representatives of the British Iron and Steel Federation joined the Board to control the developments. The plant was fully operational by 1938, but the loan was not redeemed and Bank intervention continued until 1945. A third blast furnace was built in that year, but the restricted site allowed only two furnaces to be operated at any time.

**Baldwins Ltd**

This firm started in 1849, when E. P. and W. Baldwin built the Wilden Iron Works and a water driven tinplate mill at Stourport on Severn in Worcestershire. One of their sons, Alfred Baldwin, built a tinplate works at Panteg in 1885 and the Pontymoile tinplate works at Pontipool, near to Ebbw Vale, in 1892. Both works started to make galvanised sheet in the next few years. In 1902 all of these plants merged with Wright, Butler, and Co. to form Baldwins Ltd. Wright Butler owned the Panteg and Landore (Swansea) steelworks and the Blackwall Galvanised Iron Co. in London. Alfred Baldwin became chairman of the company. His son, Stanley, became a director and later achieved fame as the Prime Minister of Great Britain.

Developments over the next three decades proceeded at a lower rate than at Richard Thomas, but were equally impressive. In 1906 the Port Talbot Steelworks, which had been built in 1901 but closed down two years later, was purchased jointly with the Gloucester Railway Co. Ltd to produce acid and basic open hearth steel. Additional furnaces, plate, and bar mills were added during the next few years. The first electrically driven tinplate mill was installed at the Kings Dock, Swansea works. To meet the demand for steel during the First World War, construction of the Margam works was started on an adjoining site to the Port Talbot works with blast furnaces, coke ovens, open hearth furnaces, and rolling mills. The Panteg works was expanded in 1917. Production was increased further in 1918 with the purchase of the Brymbo Steel Company, North Wales, Briton Ferry Iron Works near Swansea, and the Oxfordshire Ironstone Co. A new company, called the British Steel Corporation (BSC), was formed to take over the Briton Ferry works and BSC was absorbed into Baldwins in 1919. Work proceeded slowly, however, on the Margam site. Only two open hearth furnaces had been commissioned by the end of 1918 and the blast furnaces were not fully operational until 1923.

Tube production was started in 1921 with the acquisition of a controlling interest in the Mannesmann Tube Co., located in the Neath valley, which had been started
by the brothers of William Siemens. Several tinplate works were also acquired and the Elba Tinplate Co. with modern plant was opened at Swansea in 1925.

In 1928 the company formed an association with the Dorman-Long and Hoskins Steel Cos. to create the Australian Iron and Steel Co. at Port Kembla, NSW. Shortly afterwards, however, the capital value of Baldwins was written down because of the financial losses in the severely depressed market for British steel. Two years later, the Port Talbot, Margam, Brymbo and Briton Ferry plants were amalgamated with the steelworks owned by Guest Keen and Nettlefolds at Cardiff and Dowlais to form the Guest Keen Baldwins Iron and Steel Co. Ltd, to ensure survival during the recession. Baldwins Ltd continued to operate all but its iron- and steelmaking activities as an independent company until the merger with Richard Thomas. In addition to the plants producing tinplate and galvanised sheets in South Wales, this comprised the original Wilden works at Stourport and three other closely integrated works that had been built in the Midlands: the Cookley, Stour Vale and Swinden (Staffordshire) works. Stour Vale and Swinden works made terne coated sheet, while Cookley produced thick coated tin sheet and Wilden made blackplate. All four works had been involved in the production of silicon steels for electrical applications since the beginning of the century and produced over half of the British output of these grades.

Richard Thomas and Baldwins Ltd

When the Richard Thomas Co. was freed from control by the Bank of England in 1945, plans were set in train for the construction of a second and larger continuous hot strip mill to meet the rapidly increasing demand for this product. The first step was a merger with Baldwins to form Richard Thomas and Baldwins Ltd. The new company intended to develop the plant for its own resources, but escalating cost and Government restrictions frustrated the plans. Consequently, a consortium was formed with GKN, Lysaghts Ltd and Llanelli Tinplate Co. to form the Steel Co. of Wales. The Abbey works was built between 1948 and 1952 with a 1.8 m continuous hot strip mill. The Margam and Port Talbot works were modernised and transferred to the new company. A third melting shop was built containing eight 200 t tilting open hearth furnaces with a capacity to produce 1 Mt per annum. Cold rolling mills were built nearby at Trostre and Velindre. Meanwhile, RTB had built the first electrolytic tinning line in Europe at the Ebbw Vale works in 1947. A new blast furnace and additional steelmaking capacity was added at the Redbourn plant. A grain oriented electrical steel was marketed under the trade name Alphasil and the Cookley works was expanded in 1951 to manufacture an extended range of higher quality electrical steels.

The British steel industry was nationalised in 1952. In addition to its holding in the Steel Co. of Wales, the company was then operating three blast furnaces and seven open hearth furnaces at Redbourn, three blast furnaces, three Bessemer converters and five open hearth furnaces at Ebbw Vale, six open hearths and four arc furnaces at Panteg and over thirty open hearth furnaces at smaller works in South
Wales, including Cwmfelin, Gorseinon, Llanelly and Pontardawe, together with associated rolling mills for sheet, billet and bar production and surface coatings in South Wales and the Midlands. Galvanised sheet and keg material was made at the Blackwell (London) works, while components were fabricated at the Machynus Engineering works, Llanelly. The total iron- and steelmaking capacity of all these plants was markedly greater than the production criteria used to select the companies which were nationalised and Richard Thomas and Baldwins was taken into stage control.

When the industry started to return to private ownership in the following year, the Steel Co. of Wales was sold as a separate entity. Richard Thomas and Baldwins Ltd remained as the only ferrous manufacturer under Government control, but several of the company’s assets were sold to other companies.

Numerous important developments occurred during the next decade. The Cwmfelin, Goresend and Llanelly sheet mills were closed down. The Bessemer converters at Ebbw Vale were converted to oxygen-steam blowing. The first LD converter (45 t capacity) in the UK was installed in 1960 and the remaining Bessemer converters were progressively replaced by two more LD converters when the process had been developed successfully. A second electrolytic tinning line was also commissioned. Under licence from Armco, the company started producing a more advanced version of the Alphasil grain oriented 3% Si iron for electrical transformers. The steel was made and cast into slabs and hot and cold rolled at Ebbw Vale, with an intermediate continuous anneal, and finish annealed at the Cookley works. Plastic coated steel sheet was produced at the Stour Vale works. A Central Research Laboratory was opened at Whitchurch in Buckinghamshire and a management training college at Stoke d’Abernon in Surrey.

The demand for wide steel sheet continued to increase, so in 1959 plans were formulated for the construction of a new integrated plant with three 130 t LD converters and a continuous hot strip mill to produce 1.4 million tons of sheet steel per annum on a greenfield site at Llanwern, near Newport. Since the company was still in state ownership, it was able to secure Government funding of £70 million to build the plant and it came into production in 1962. It was originally named Spencer works after the then chairman of the company. Three years later both the Llanwern and Ebbw Vale works were producing over 1 Mt of steel per annum, so the remaining cold metal melting shops were closed down. The Panteg works had been modified to produce alloy and stainless steels and a continuous casting plant was commissioned there for the production of stainless steel sheet. A rotor pre-refining furnace, new coke ovens and a continuous billet mill were installed at the Redbourn works. A new sheet metal processing plant was built at Gorseinon to expand the production of the Cwmfelin (Swansea) Fabrication Works.

The British iron and steel industry was re-nationalised in 1967 and the name Richard Thomas and Baldwins Ltd was consigned with many other well known names in the industry to history. The Llanwern and Ebbw Vale plants have continued to increase throughput and in 1996 accounted for almost half of the wide steel sheet and tinplate production by British Steel. Most of the other production
units have been demolished. Electrical steel production was transferred to the Orb works at Newport in 1980 and only the Cookley works survives from the original Midlands electrical steels group to manufacture terne coated sheet.

SKINNINGROVE IRON CO. LTD

BY C. SHEPHERD

There can have been few iron- and steelworks sites in the UK to match the dramatic setting of the Skinningrove works, with its location on the North Yorkshire coast high above the North Sea, some 7 km south east of Saltburn-by-the-Sea. At first sight it seems an unusual position to choose for such a works but there were sound historical reasons for its development.

While small amounts of ironstone had been removed from the foot of the cliffs along the coast for a number of years, it was not until 1848 that the Roseby brothers began to extract Cleveland ironstone from the side of the valley near the mouth of Skinningrove Beck; the first shipment being despatched from the beach to Middlesbrough and on to Witton Park furnaces on 26 August 1848. Messrs Bolckow and Vaughan soon took over the lease for the mine but only modest amounts of ironstone were produced as they concentrated their attention on the Eston Mine, which was nearer their work on the banks of the River Tees. Also, at Eston they did not have to contend with the vagaries of the sea to ship out ironstone.

With the growth of the iron industry adjoining the Tees, based on the availability of local ironstone in the Cleveland Hills, the competing railway companies looked to extend their lines to reach the more remote sources of ironstone. The section of the Cleveland Railway from Guisborough to Skinningrove was authorised in 1858 and finally opened to Carlin How, near Skinningrove, in 1865. In the same year, Messrs Pease and Partners began to work the main seam of Cleveland ironstone at the Lofthouse Mine (later called Loftus Mine) in the Skinningrove Valley. Other mines opened in the area in the next decades making use of the new railway to send their output to the ironworks on Teesside.

Despite fluctuating economic conditions, the early 1870s was a period of major expansion in the Cleveland iron trade and in 1873–1874 the Lofthouse Iron Co. erected two 85 ft high blast furnaces on the clifftop above Skinningrove village. These furnaces were comparatively large for the period and were equipped with very thick linings and 8 ft diameter hearths. A contemporary comment on the choice of location is given in The Engineer magazine on 28 August 1874: 'There is good reason for believing that pig iron can be made cheaper here... It requires 3.5 tons of iron ore to make a ton of pig iron, but it only needs 20/25 cwts of coke for this amount of iron'; the proximity of the Lofthouse Mine was an obvious attraction.
The furnaces were blown in on 17 October 1874 and the works is reputed to have produced pig iron 2 shillings a ton cheaper than that of any other firm on Teesside. Unfortunately this success was short lived. It soon got into difficulties and the Kennedy family of Ulverston and its associates, who had formed the Lofthouse Iron Co., had to put the business in the hands of the banks. The furnaces were shut down in 1877.

Myles Kennedy then turned to Thomas Charles Hutchinson who had considerable knowledge of the Cleveland iron trade. When he was fourteen, Hutchinson had started work with Pease and Partners in Middlesbrough. He later joined Fox, Head and Co. Ltd, which had a rolling mill at Newport, Middlesbrough, eventually becoming its commercial manager. With Myles Kennedy and others, Hutchinson purchased the Lofthouse Ironworks and an ironstone mine at Carlin How for £50,000. They formed the Skinningrove Iron Co. Ltd in 1880 and brought the furnaces back into blast in 1881. Hutchinson was to be a key figure in the successful establishment of the Skinningrove Iron Co. and was its Managing Director from 1880 to 1918.

The main output of the works during its early years was foundry iron and the principal market for this material was located around Falkirk and Glasgow, where the trade was enjoying great prosperity. Transporting the iron to Scotland involved a long rail journey, so a decision was taken in 1882 to construct a jetty at the foot of the cliff and connect it to the works by a railway incline, in order that the pig iron could be transported by ship. For building its curved jetty, the company made a successful hydraulic cement using hydrated slag and lime. Exposure to northeast gales meant that it was not until 1888 that the jetty was sufficiently completed for the first pig iron shipments to be loaded on to the chartered vessel, 55 Runswick. In November 1891, the owner of the Runswick withdrew from the charter and the Skinningrove Iron Co. purchased its own ships to carry on the trade.

An expansion of the iron producing capacity took place when two further blast furnaces were erected in 1894, followed by a fifth in 1897. From then on, it was usual for four of the five furnaces to be in blast. The new furnaces had an increased hearth diameter of 10 ft and the stack and hearth linings were 4 ft thick. These furnaces were constructed in line with the two original structures. Steam was a major requirement to power much of the plant at the works and a battery of thirteen Lancashire boilers was installed between 1894 and 1907. The capital of the company was increased to £60,000 in 1894 and to £200,000 in 1900. Annual output of pig iron from the works at this time was 150,000 tons.

By the early 1900s, it was becoming clear that the works could no longer rely on sales of pig iron for its main income. Cast iron and wrought iron were increasingly being replaced by steel for many types of goods and for construction. Steelmaking was by then well established at some of the works on Teesside (commercial bulk steel manufacture had begun there in 1877) and T. C. Hutchinson decided that this example had to be followed.

In 1907 the company’s issued share capital was increased to £300,000 and a start was made on installing new steelmaking plant of the latest design. A 200 ton Talbot
tilting basic open hearth furnace was installed. Benjamin Talbot was a director of the South Durham Steel and Iron Co. who, in 1905, had successfully introduced his 'continuous' steelmaking technique at the Cargo Fleet Iron Co.'s works. New melting shops and rolling mills were provided at Skinningrove, with the first steel ingots being produced in July 1910 and rolled products following in 1911. Two batteries of Otto regenerative coke ovens also came into operation in 1911, when they were stated to be 'the first of their kind in Britain'. The capacity of the cokemaking plant was doubled during the First World War.

There had been a strong German influence in the choice of equipment during the establishment of the steelworks; for example, Erhardt and Sehmer engines, designed to run on blast furnace gas, had been installed and the large electrically driven reversing mills were based on the original design at Rheinhausen. The Skinningrove plant consisted of a 42 in cogging mill, with 36 in roughing and finishing stands driven in tandem by a single motor. Not only was the motor hailed as the largest in Britain in 1911, the Ilgner system at Skinningrove was about the second to be installed in this country for dealing with highly fluctuating loads, as distinct from continuous loads. Cargo Fleet works had started shortly before using the Kramer system, so Skinningrove was historically the third in Britain to introduce electric drive for the reversing rolling mills.

An important feature of the Skinningrove works was its efficient use of energy. This was encouraged because of its greater distance from the Durham coalfield, compared with its competitors on Teesside. An indication of the pioneering work carried out at Skinningrove was given in a talk on 'Flameless combustion' by Carleton Ellis presented to a meeting in New York in 1912. He went on to say:

'That the gas-firing of boilers according to the new system has been advanced beyond the mere experimental stage is proved by the recent erection by the Skinningrove Iron Works Co. Ltd, Chuland [sic], Yorkshire of a 110-tube boiler capable of evaporating not less than 5500 lb of water per hour, fired by gas from a new installation of coke ovens adjacent to the blast furnace.'

The steelmaking furnaces made use of producer gas as a source of heat. This was supplemented by the addition of coke oven gases and Bainbridge says that the 'shop was successfully operated on these lines for some time until it was considered expedient to discontinue use of the coke ovens (circa 1933) which necessitated reversion to the use of producer gas'. By the 1920s, coal was mostly brought in for the regenerative coke ovens, with much reliance being placed elsewhere in the works on the use of waste gases as a source of power.

The initial output of the mills was sections for the construction and shipbuilding industries, with railway lines subsequently being added to the range of products. The first 90 ft long rails in Britain were rolled at Skinningrove in 1929 for the London and North Eastern Railway main line at Thirsk, to be followed by the subsequent testing of some 120 ft long rails also produced at Skinningrove.

With the onset of the First World War, production had turned to meeting the
demands of the conflict, and the manufacture of shell steel became important. In 1914, two more tilting steel furnaces, each having a nominal capacity of 90 tons, were added to cope with the demand. After they were installed, it was not considered practical to continue using hot direct metal and, between 1914 and 1919, the large furnace operated as a mixer. Further additions were made to the steel plant in 1919, when a 400 ton mixer was installed, and the large furnace reverted to the production of finished steel. Minor modifications over the next 20 years meant that the large furnace had a nominal capacity of 240 tons and the two smaller furnaces 100 tons each.

During the First World War, part of the byproducts plant was used to manufacture the explosive trinitrotoluene (TNT). Two nitrators were erected near the edge of the cliff, based on the theory that at least some of any accidental explosion would be dissipated over the sea!

T. C. Hutchinson died in 1918 while still in control of the works and was succeeded by his son, Alfred, who had previously served as Secretary and Assistant Managing Director. Trading conditions after the war were very difficult. Pease and Partners had been closely associated with the Skinningrove works, both as shareholders and suppliers of ironstone, and between 1922 and 1932 the works was leased and operated by them, although the name Skinningrove Iron Co. Ltd was retained and Alfred Hutchinson remained in control.

The Skinningrove Iron Co.'s issued share capital had been increased to £400,000 in 1917 and these new shares were mostly acquired by two structural engineering companies: Guest Keen and Nettlefold Ltd and Redpath Brown and Co. Ltd. The latter had taken a 25% interest in Skinningrove to safeguard its supply of steel. A simple fabricating plant was installed at the works. By 1921 the collapse of demand meant that there were adequate supplies of steel available and buyers could pick and choose where they obtained their supplies. As a result the fabrication operations were reduced, although Redpath Brown remained shareholders.

As the depression grew steadily worse, the works struggled to keep going. The range of products was increased and the 36 in mill began to roll small joists and angles. By the early 1930s, the works was even importing sections made in Belgium and bending them into colliery arches for use in British coal mines. In October 1933, the Skinningrove Iron Co. made the brave decision to improve efficiency by carrying out an extensive modernisation of the works which involved a complete shutdown between November 1933 and March 1934. It meant that 2000 employees were temporarily out of a job, as were the 1000 people at the local ironstone mines. The works reopened in April 1934 with the more efficient equipment and a revamped selling organisation. In 1936, two of the old blast furnaces were demolished and replaced by more modern units, although these were still hand charged. An 18 in mill was installed in the following year, capable of rolling smaller, light sections more economically than the 36 in mill. Trading conditions were far more buoyant, especially as rearmament programmes got under way. By the end of the decade, the works enjoyed full employment and full order books.

During the Second World War, the works came under the control of the Ministry
of Supply and produced steel for shells, as well as welded sections for Bailey bridges, ordnance factories and invasion barges. It was during the war that two men came to the works who were to have a major influence on its fortunes during the next twenty years. These were Richard Mather (Chairman 1942–1962) and Gilbert Debenham (General Manager, later Managing Director 1942–1962, Chairman 1962–1967). In 1953, Richard Mather was awarded the Bessemer Gold Medal of The Iron and Steel Institute.

The years after 1945 were dominated by discussion about the nationalisation of the country’s iron and steel industry. A five year development plan submitted by the British Iron and Steel Federation to the Ministry of Supply put forward proposals for rationalisation and expansion of output. Despite being regarded as a cost effective plant, Skinningrove’s role as a small integrated iron- and steelworks did not fit easily into the proposals and it was considered to have no long term future, the report stating that any investment in Skinningrove should have regard to its possibly limited life. This prompted a vigorous campaign, which drew attention to the good performance of the works and the dire consequences for East Cleveland if it closed. In 1947, the Skinningrove Iron Co. ceased to be a subsidiary of Pease and Partners, although the latter continued to be the largest shareholder. The colliery interests of Pease and Partners had been disposed of with the nationalisation of the coal industry and it was, therefore, logical for the Skinningrove Iron Co. to take over the Loftus Mine, thus ensuring its continued supply of local ironstone. Demand for steel was increasing and the company’s issued share capital was increased from £900,000 to £1275,000.

When the first nationalisation of the iron and steel industry took place in 1951, Skinningrove became the property of the Iron & Steel Corp. of Great Britain. This situation only lasted ten months because a new Conservative Government came in and stopped the nationalisation. The Iron and Steel Holdings Realisation Agency was set up to dispose of the assets of the corporation. Some of the major plants were the first to move back into the private sector but Skinningrove was not disposed of until February 1963 when it passed to Iron and Steel Investments Ltd, a consortium comprising ten of the leading steel companies in Britain.

In the meantime, the buoyant demand for steel had forced the Government’s hand and it was agreed that the modernisation of Skinningrove works should proceed. The most significant improvement was to iron production. In the years immediately after the Second World War, the works had relied on two hand charged blast furnaces. These were supplemented by a brand new blast furnace with a 21 ft diameter hearth commissioned in 1952 and capable of making 5000 tons of iron per week. Oil injection was installed on this furnace in 1966.

Improvements were carried out to the steel furnaces, the active mixer being converted into a 300 ton tilting furnace. A 600 ton inactive mixer was also installed, although this was replaced in 1957 by direct oxygen blowing of molten iron in 60 ton ladles to remove silicon, before its charging to the open hearth furnaces. This practice was abandoned as unnecessary a few years later when the construction of
the new sinter plant in 1961 resulted in steel plant feed of improved composition. The mills were also substantially modernised.

Skinningrove works ceased to be part of Iron and Steel Investments Ltd on 28 July 1967 when the ownership of the fourteen major steel companies was vested in the British Steel Corp. The works became part of the new nationalised undertaking but it was not long before BSC began to rationalise its iron production facilities by concentrating on a limited number of large blast furnaces located close to deep water berths. The new basic oxygen steelmaking plant was also opened in 1971 at Lackenby on Teesside and this was able to supply steel blooms to Skinningrove. As a result the remaining Skinningrove blast furnace was taken off blast in September 1971 and the steel plant at Skinningrove closed in March 1972.

It was not the end for Skinningrove, however, because BSC recognised that there was still a need for a small works producing specialist sections for the earthmoving, material handling, and shipbuilding industries. It is uneconomic for the large mass production mills to handle this sort of order and this has sustained Skinningrove’s existence during the past 25 years.

Steel blooms are now brought by rail from Lackenby for rolling. In the late 1980s, the Skinningrove works was capable of producing over 250 special sections, with 70% of the output being exported mainly to the USA, mainland Europe and Canada. At that time a £20 million modernisation programme was carried out in the 36 in mill, including new roughing and finishing stands, and an intermediate walking beam reheating furnace. A subsequent continuing programme of improvement coupled with the efforts of its skilled workforce, has enabled the Skinningrove works to develop an enviable reputation for producing high quality special sections.

Acknowledgements

The assistance of J. K. Almond, who has contributed to the text, and L. Harker from the Skinningrove works, is gratefully acknowledged.

STEWARTS AND LLOYDS LTD

BY C. BODSWORTH

The gradual replacement of the waterwheel by steam power for driving machinery in the early years of the nineteenth century created a demand for tubes for use in boilers and steam transmission systems. The development of factory manufacture, coupled with the growth of the railways in the middle years of the nineteenth century, resulted in a rapid escalation of this market. There was also an increasing requirement for pipes to transport gas, water and sewage. To meet the demand many new companies were founded with the sole objective of pipe and tube
manufacture. Two of these companies started on a small scale, and bought out competitors and then merged together to form a combine which eventually dominated the British market for tube supplies.

**Lloyd and Lloyd**

This was the name of the firm created by Samuel and Edward Lloyd when they opened the Albion Tube Works in Birmingham in 1859 for the manufacture of boiler tubes. In 1870 the company merged with the Coombs Wood Tube works of Henry Howard and Co. at Halesowen, which made screwed and coupled wrought iron tubes. Coombs Wood then became the main site for expansion and for the development of new processes, including the first successful gas welding of large diameter tubes made in wrought iron and in steel. Electrical welding of flanges and fittings was perfected in the 1890s. The firm became a private limited company in 1899 and in the following year a base in Scotland was established with the purchase of the Clydeside Tube Co., Glasgow, a manufacturer of boiler tubes and fittings.

**A. and J. Stewart**

The company was founded in 1862 when Andrew Stewart, who had opened the Clyde Tube Works in Glasgow in 1860 to make butt and lap welded wrought iron boiler tubes, took his brother James Stewart into partnership. The business grew rapidly. A move was made to larger premises in 1867 and a limited liability company was formed in 1882. In a backwards process integration, the Clydesdale Iron and Steel Co. at Mossend was acquired in 1890 to provide the steel required for tube fabrication. This works had produced wrought iron strip from 1871 and started to produce steel in 1884. New rolling mills for strip production were now installed. The enlarged company traded as A. & J. Stewart and Clydesdale Ltd.

Eight years later this company merged with James Menzies and Co., who manufactured hollow drawn, seamless tubes at the Phoenix Tube Works, Rutherglen and the name was change once again to A. & J. Stewart and Menzies Ltd. A new works for the production of lap welded pipes of large diameter was opened at Airdrie in the same year.

**Stewards and Lloyds Ltd**

When these two companies merged in 1903, to become the largest tube maker in Great Britain, the Stewarts and Lloyds Ltd name was adopted. The total production of 80,000 t of tubes in the year of the merger was almost trebled in the next decade by rationalisation and expansion of the works and with further acquisitions of competitor companies. The Sun Foundry, to produce steel castings using Tropenas side blown converters for metal melting, was opened in 1906 in the Sun Tube Works, Coatbridge, which A. & J. Stewart had purchased in 1882. The Vulcan Tube Co. at
Motherwell was purchased in 1912 to provide facilities for the production of pipes and tubes up to 2 m in diameter and the Clydeside Tube Co. was opened at Tollcross to make seamless boiler tubes up to 100 mm in diameter.

Construction of the Calder Tube Works was started in the following year on the site of the original Scottish works bought by Lloyd and Lloyd. This was intended to operate as a seamless steel tube mill, but the First World War intervened before construction was completed and it did not achieve full production until a decade later. In contrast to the experience of most British steelworks, there was no significant expansion of the company’s manufacturing facilities during the war years, but a large part of the capacity was diverted to the production of gas cylinders and shells.

Although the Lloyd and Lloyd company had originated in the English Midlands, most of the new plant and developments were located in Scotland during the two decades following the merger to form Stewarts and Lloyds. The first step in a chain of events which led eventually to a major relocation of the manufacturing operations to the English Midlands was taken in 1917, when a controlling interest in the North Lincolnshire Iron Co. was acquired to provide a supply of pig iron. Several collieries were also purchased.

These acquisitions did not satisfy completely the basic requirements so, in 1920, a controlling interest was bought in the Bilston, West Midlands works of Alfred Hickman Ltd. This plant had been developed from the nucleus of the Bilston ironworks (which had started production in about 1790) and the Spring Vale blast furnaces. Hickman bought these works in 1866 and installed puddling furnaces and rolling mills. The mills were regularly updated. Steelmaking started there when three 5 t Bessemer converters were transferred in 1883 from the defunct Mersey Steel and Iron Co. to the Staffordshire Steel and Ingot Co., which Hickman constructed on a site adjacent to his blast furnace plant. A 7 t open hearth furnace was added soon afterwards. The company also had a controlling interest in the Oxfordshire Ironstone Co. Ltd and in 1919, had purchased the Lloyds Ironstone Co. Ltd at Corby. At the time of the purchase by Stewarts & Lloyds, the works contained three blast furnaces, three basic Bessemer converters, three 80 t basic open hearth furnaces, and a hot metal mixer. A Morgan 11 stand continuous hot strip mill with an annual capacity of 150,000 t of strip was now added. The mill became fully operational in 1923 and the remaining shares in the Alfred Hickman company were purchased the following year. The Bessemer converters were replaced by additional open hearth furnaces in 1925. In the same year an automatic mill for the production of hot rolled seamless tubes was opened at the Tollcross works and a large universal mill was commissioned at the Clydesdale works.

A number of ironworks in Scunthorpe and elsewhere in the Midlands had perfected a blast furnace practice of blending the low grade calcareous Lincolnshire iron ores with the siliceous ores from Oxfordshire and Northamptonshire to form a self-fluxing burden and reduce the need for fluxes. Investigations now indicated that a self-fluxing charge could be compounded primarily from the different seams in the Northamptonshire ore bed. The high phosphorus content of the ore made the
pig iron produced suitable for refining in the basic Bessemer converter. This process had been extinct in Great Britain since about the time when the Bilston converters were scrapped. However, the cost of production was low in comparison with the open hearth process and the quality of the rimming and bottle top steels made in the converter was adequate for most of the types of pipes and tubes that the company produced. In fact, Bessemer steel was being imported from the Continent for use in the Scottish works on occasions when the demand for tubes exceeded the steelmaking capacity of the company’s works. An increase in steel production was required, so a resumption of Bessemer converter operation was considered.

A development report was commissioned in 1930 from H. A. Brassert & Co., a firm of American consultants. This recommended the construction of an integrated works on a greenfield site to utilise the Northamptonshire iron ores with blast furnaces, Bessemer converters, open hearth furnaces and appropriate fabrication equipment. The recommendations were accepted by the company and plans were eventually prepared for the construction of a major new iron- and steelworks at Corby to utilise the ores obtained from the Lloyds ironstone quarries.

Despite the difficult trading conditions experienced by the iron and steel industry, the company secured loans from the Bankers Development Corp. for the construction of the new works on the assurance that the steel produced would be used exclusively for tube production and not sold in bar or sheet form. Work started in 1933 on the erection of four blast furnaces with 6 m diameter hearths, a sinterplant, coke ovens, and a melting shop containing two 1000 t inactive metal mixers feeding four 25 t basic Bessemer converters and three open hearth furnaces. Provision was made for re-circulation of part of the converter slag to the blast furnaces to increase the phosphorus content of the iron and so enhance the heat available during refining in the converters. The rolling facilities included a blooming mill, a 0.8 m reversing mill and a 0.6 m tandem billet mill. Strip was produced from a 0.6 m continuous mill. Solid drawn tubes were to be made on a Mannesmann push bench, while strip steel was initially formed into tube by passing through sets of curved rolls and pressure welded by the Fretz Moon process. A galvanising line was provided for coating the finished tubes.

A new town was built around the village of Corby to house the staff and workers who were relocated there from the Scottish plants. The Vulcan works in Motherwell was closed in 1932. Steelmaking ceased temporarily at Clydesdale Iron and Steel in the following year, making large numbers of people available for transfer, and the plate mill was transferred to the Corby plant. To maintain production while the new plant was under construction, from 1932 to 1934 acid Bessemer slabs and billets were despatched daily by train from the Workington Iron and Steel Co. in Cumbria to the Bilston works.

The first blast furnace at Corby was blown in during 1934. In the same year the Central Research Department, which had been opened in Glasgow in 1929, was relocated in new premises at Corby. The first heat of converter steel was blown in late December 1934 and most of the rolling and tube mills were fully operational in
the following year. The annual capacity of the Corby works was then about 400,000 ingot tonnes of steel. A fifth converter and a third mixer were installed a few years later, raising the capacity to a little over 0.5 Mt.

Export sales had always featured strongly in the company’s order book and a manufacturing facility which had been opened in 1928 in South Africa had proved successful. New works were now opened in Australia (1933) and India (1935).

As the steel trade recovered from the effects of the depression in the 1930s, the company resumed its policy of buying out its competitors. The Scottish Tube Co., which had been formed in 1912 by the merger of several older companies, was acquired in 1931 and four of its subsidiary works were closed in the following year when the Motherwell plant was closed. The works of John Spencer Ltd, founded in 1847 at Wednesbury, was purchased in 1935. On this site, over a century earlier, the first screw jointed gas pipes has been produced.

The British Mannesmann Tube Co. at Newport was acquired from Baldwins Ltd in 1936 as a joint purchase with Tube Investments Ltd and re-named the Newport and South Wales Tube Co. The British patent rights for the Mannesmann billet piercing process had been purchased by C. W. Siemens and his brother and the works was erected on the site of Siemens’ Landore steelworks in 1888. Following liquidation in 1899, the works were re-opened under the direction of Max and Richard Mannesmann. Expansion of the plant could not be accommodated at the Swansea site, so in 1919, a new works was opened at Newport in South Wales to produce tubes using steel supplied from the new Margam works of Baldwins Ltd. Baldwins bought up the Landore and Newport works in 1921.

Jarrow Tube Works Ltd was also formed as a joint venture with Tube Investments in 1938. The Stanton Iron Co. Ltd, who, in 1919, had pioneered the production of centrifugally spun cast iron pipes, was bought out in the following year. The first blast furnace at Stanton had been blown-in in 1846. The company had bought out the Holwell Iron Co. Ltd, Melton Mowbray in 1918, Ridings Ironworks Ltd, Alfreton in 1920, the Wellingboro Iron Co. Ltd in 1932 and Cochrane & Co. Ltd, Middlesbrough in 1933. By the date of the acquisition by Stewarts and Lloyds, Stanton was the largest producer of foundry grade pig iron in Britain.

By this stage, Stewarts and Lloyds controlled more than three-quarters of the total British production of pressure pipes and tubes made from cast iron and plain carbon steel, while Tube Investments dominated the production of alloy and precision fine bore tubes.

In 1937 the Lancashire and Corby Steel Manufacturing Co. Ltd was formed in association with the Lancashire Steel Corp. Ltd. The new company produced cold rolled strip in a new rolling mill on the Corby site from Bessemer steel ingots produced at Corby and from slabs supplied by Irlam, while blooms were sent from Corby for rolling into bar at the Irlam and Warrington works.

The major development during the Second World War was the construction of a melting shop containing two 25 t arc furnaces at Corby to produce alloy steels for armaments. A new type of hydraulic forging press had been designed and built for the production of steel shells which required no subsequent internal machining.
The first press was built at the New Crown Works, Wednesbury in 1938. Twenty-three additional machines were installed there in the next few years and others were supplied to ordnance factories in Britain and abroad. The company was also the major producer of the 1600 km of 75 mm bore steel pipe with 12 mm wall which was used in the construction of Pluto (pipeline under the ocean) in 1944 to carry petroleum from Southampton via the Isle of Wight to supply the allied forces who had landed in Normandy.

The total pig iron production by the company was approximately 0.8 Mt in 1945, one-quarter of which was smelted in three 6 m hearth blast furnaces at Bilston and the remainder at Corby. This total was almost identical to the immediate pre-war output. Steel production had increased to about 0.8 Mt during the Second World War as a result of increased output from the seven Bilston and six Clydesdale open hearth furnaces and with the start of scrap melting in the electric arc furnaces which increased the steel output at Corby.

The plant capacity increased progressively during the next two decades. An ore bedding plant was installed at Corby in 1948 to improve the consistency of the blast furnace feed. The majority of the ore was still charged to the furnaces without calcining, and sinter comprised only about 25% of the ore feed. This proportion increased steadily over the next decade as new ore preparation plant came on-stream and reached 70% of the burden by the late 1950s.

Several developments came on-stream in 1949. These included a new melting shop containing two 110 t fixed open hearth furnaces at Corby; the Clydesdale works was almost completely rebuilt and four new open hearth furnaces were commissioned there, and a 400 mm seamless tube mill was installed at Clydesdale. A new continuous weld mill for production of tubes up to 100 mm diameter was installed at Corby. A new company, S. & L. Minerals Ltd, was also formed to manage the company’s iron ore quarries which were annually extracting about 4.5 Mt of ore. The first electrical resistance weld mill was installed at Corby in 1951.

The total steel production had increased to 1.2 m ingot tonnes and the company was the sixth largest steelmaker in Great Britain before it was taken into state ownership when the industry was nationalised in 1951. It reverted to its previous status when the Nationalisation Act was rescinded in the following year.

A new steel foundry was built at Tollcross in 1954 to replace the old Sun Foundry. In the same year a new blast furnace with 7 m diameter hearth and operating with high top pressure replaced two of the older furnaces at Bilston. Over the next decade the melting shop there was redesigned to house seven 100 t open hearth furnaces fed by two 1000 t inactive hot metal mixers and a vacuum degassing plant was installed.

A 1.2 m blooming mill, commissioned in 1958, raised the rolling capacity at Corby to over 1,500,000 ingot tonnes per annum and tube production was increased by the installation of additional continuous weld mills and cold draw benches.

The Bessemer converters at Corby had given good service and the quality of the steel had been progressively improved. In particular, the nitrogen content had been
lowered by redesigning the shape of the converters to give a shallower metal bath and by supplying part of the oxygen required for refining in the form of iron ore and millscale in place of the conventional scrap metal coolant. But it was proving difficult to meet the increasingly more stringent property requirements which were being specified for steel tubes towards the end of the 1950s. Plans were made accordingly to replace the Bessemer vessels with three 100 t LD ac converters. The new plant was commissioned in July 1965 and on 22 January 1966 the last basic Bessemer blow at Corby (and in Great Britain) was completed as the third LD converter came into production.

In 1965 the company produced just over 2 Mt of steel and had moved up the ranking to become the fifth largest steelmaker in Great Britain. This was well above the threshold set for state ownership when the industry was renationalised in 1967 and the Stewart and Lloyd company ceased to exist. The Corby strip mills were incorporated into the Strip Mills Division of British Steel Corp. and the remainder of the works was transferred to BSC's Tubes Division.

JOHN SUMMERS AND SONS LTD

by C. Bodsworth

Little is recorded about the early life of John Summers, but it is known that he opened a small ironworks in the early 1860s. He died in 1876 and the business was continued by his sons and grandsons. When measured in terms of tonnage output, the company had grown to become one of the larger British manufacturers of iron and steel by the time that the industry was nationalised in 1967. In a rare achievement for the industry, except for a 10 year period from 1938, the company remained under the control or one or more of the direct descendants of John Summers throughout that period. An illustrated history of the company has been published recently.16

Globe Works

John Summers built the Globe works at Stalybridge near Manchester, with puddling furnaces and hand rolling mills for the production of clog irons and nails. The wrought iron trade grew steadily, but by the early 1890s production had diversified to include the rolling of steel sheets from bought-in bars. The sheets were sold to a galvanising company on Merseyside. Recognising the potential for development, Harry Summers persuaded his brothers to install a galvanising pot and they produced their first zinc coated steel in 1894. No space remained to expand production on the restricted Globe works site so a 40 acre plot was purchased for the construction of a new works at Hawarden Bridge on the banks of the river Dee in Flintshire, North Wales. This was a bold decision at the time, for the site was a marshland which required raising and levelling. Local collieries supplied steam coal, but there
was no other significant industrial or residential development in the area. It was coastal site and the Liverpool docks were only a little over 20 miles away by sea, but the estuary of the river Dee was navigable only by a very small coastal boats. A railway line skirting the site provided the principal means of access.

**Shotton Works**

The new works, which was later to take the name of the nearby village of Shotton, began the production of galvanised and corrugated steel sheet in 1896. A limited company was formed in 1898 with a share capital of £200,000. All the shares were held by members of the Summers family. By that time the two works were producing 40,000 t of zinc coated (galvanised) sheet per annum.

The steel bars required for rolling into sheet were mainly imported from Pittsburgh, PA, USA, but problems arose from irregular deliveries, so the Summers brothers decided to integrate the process backwards. Construction of a melting shop with nine 50 t open hearth furnaces operating a cold metal practice was started in 1902. A bar mill for initial reduction of the ingots and additional sheet rolling mills were also installed. But large quantities of subsidised semi-finished steel imports severely curtailed the market for British steelmakers during the early years of the new century. Completion of the melting shop was delayed, therefore, until the dumping of steel from overseas was ended and the plant was not fully operational until 1908. In the following year, the Marsh mills extension was opened with an additional twelve rolling mills, increasing the output to 4500 t/week.

At the start of the First World War, forty-nine rolling mills were in use and the works was fully occupied in producing galvanised, corrugated sheets for lining army trenches and for the construction of Nissen huts and shelters. The melting shop was unable to cope with the demand for steel, so a Government loan was obtained for the construction of a second melting shop, containing eight 70 t open hearth furnaces, plus a second bar mill. Construction started in 1917 and the plant was fully operational in the following year, bringing the melting capacity up to 500,000 t/year. The Wolverhampton Corrugated Iron Co., at Ellesmere Port was bought out, adding twenty sheet rolling mills to the production capacity, and the Castle Fire Brick Co. at Buckley was purchased to secure a supply of refractory materials.

**Shelton Works**

The backward integration of the company was taken a step further in 1920 when the Shelton Iron, Steel and Coal Co. Ltd, Stoke on Trent, was acquired to secure the supply of pig iron required for the melting shops. The Shelton works started production in 1841 when the first of three blast furnaces was blown in, using local iron ore and raw coal for the charge. Ten years later a fourth furnace was added, three more were under construction nearby on the Etruria site (so named after the adjacent pottery founded by Josiah Wedgwood), and a wrought iron works with puddling furnaces, forges and rolling mills was in full production.
Shelton Iron and Steel became a limited liability company in 1866 with a share capital of £250,000, but the blast furnaces remained under the direct control of the founder of the company, Earl Granville. Steel production was started with the erection of a melting shop containing two 15 t open hearth furnaces in 1888. Three more furnaces were added in the next decade. A 760 mm wide rolling mill was installed in 1892 to supplement the forge trains and the bloom, bar and plate mills. Wrought iron was still being produced, with fifty-nine puddling furnaces on the Shelton site and twenty-eight at Etruria Works. The company name was changed again to include coal in the title when the blast furnace plant was transferred to the limited company in 1899 and the share capital was increased to £500,000. A new melting shop containing three open hearth furnaces was built in 1905 and a fourth furnace was added in 1908. The first battery of coke ovens became operational in 1906. Various modifications were made during the First World War to increase the production of shell steel, joists and angles.

With the return of peace and a decrease in the demand for the products, the company welcomed the buyout by John Summers. An immediate start was made to modernise the blast furnace plant. A new, larger furnace was built, followed by enlargement of two of the original furnaces, giving a pig iron capacity of 6000 t/week by 1924. The remaining blast furnaces, together with the puddling furnaces and forges, were demolished. The new blast furnaces continued in use until 1978.

**Shotton and Shelton Works after 1925**

In the immediate aftermath of the war, the Shotton plant was fully stretched to meet the export demand for galvanised steel sheets, but the demand dropped rapidly as overseas competitors increased production in the mid 1920s. An attempt was made, therefore, to diversify into the production of sheet steel for motor car bodies, a new and rapidly growing market. Experiments continued for several years, working in close collaboration with the American Rolling Mill Co. (Armco), but it was eventually conceded that good gauge control and a satisfactory surface finish could not be obtained with the old hand rolling mills. The continued decline in orders during the depression led eventually to the closure of the melting shops in 1931 and they did not re-open until towards the end of 1933. The rolling mills and galvanising plant remained operational with a restricted output.

As the trade recovered with the introduction of the Tariff Act to protect the British industry, a fresh attempt was made to produce high quality cold rolled strip. A 1 m wide Sendzimir cluster mill, the first in the country, began production in 1936. A hot dip galvanising line was installed in the following year and the product was marketed under the trade name 'Galvatite'. Following the successful commissioning of the first British continuous hot strip mill at the Ebbw Vale works, the company engaged the Mesta Machining Co. of America to construct a 1.5 m wide continuous hot mill at Shotton, comprising three roughing and five finishing stands, with a design capacity of 500,000 t/year. A 1 m slabbing mill and a 1.5 m
three stand cold rolling mill completed the project. The cost of construction exceeded the company’s resources and a funding package of £2.2m was organised by the Bankers Industrial Development Co. (BID). Half of the loan was provided by the United Steel Cos. Ltd, who had been contemplating a development into the sheet steel trade. Thus began a long period of collaboration between the two companies. The control of John Summers passed to a committee chaired by a nominee of the Governor of the Bank of England, which remained in control until the loan was redeemed in the late 1940s. The new mills came into production in 1939, just at the start of the Second World War, but the hand mills continued in use for some time to meet the demand for sheet steel for the construction of Anderson and Morrison air raid shelters. Annual steel production during the war years averaged 0.6 Mt.

With the return of peace the company was able to resume the production of deep drawing grade and galvanised sheet steel. An electrolytic zinc coating line came on stream in 1947, the product being marketed as ‘Zintec’. In the same year, Government permission was given for the construction of a new melting shop to replace the old open hearth furnaces. It was decided that the Shotton works should be fully integrated with blast furnaces on site to allow a hot metal practice to be operated in the new melting shop. Dutch engineers were engaged to reclaim an area of the marshes by dredging sand from the Dee estuary and, in a novel development for this country, a blast furnace with an 8.2 m diameter hearth was built on a concrete raft resting on the sand bed. A second blast furnace of similar design (the largest in Europe at that time) was completed by 1953. In the same year, the new melting shop containing eight 150 t open hearth furnaces started production. The old melting shops were demolished.

The company was subjected to compulsory purchase by the Government in the first nationalisation programme in 1951. When private ownership was restored in 1954 the United Steel Cos. Ltd repurchased its holding in the company, but the shares were sold in 1961 to finance expansion within United Steels. Four more open hearth furnaces were built in 1956, increasing the annual capacity of the works to 1 Mt. The production of coated sheet steel expanded steadily. A novel development was the production of sheet which was given a coloured coating of PVC on one side and galvanised on the other side. This was marketed as ‘Stelvetite’. Zinc remained the principal surface coating, however, and four Galvatite continuous galvanising lines were in operation by 1959. Over the next few years, a 1.4 m four-high cold rolling mill, a new temper mill and two additional stands in the hot mill finishing train were installed.

The Shelton works ceased to supply pig iron to Shotton when the Shotton blast furnaces started production. The Shelton melting shop was antiquated, so a new melting facility was built on the site, incorporating two 55 t Kaldo rotary converters which were fed via a hot metal mixer from the three blast furnaces. Ingot casting ceased and the plant was the first in the world to achieve 100% continuous casting of all the molten steel produced. The first heat from the new melting shop
was produced in 1964. Two years later a universal beam mill was commissioned. The open hearth furnaces and the 760 mm rolling mill were demolished.

In 1964, the John Summers works produced 1.7 Mt of steel and the company was the eighth largest steelmaker in Great Britain. Three years later the company name was consigned to history when the industry was nationalised for the second time. Subsequently, the Shelton blast furnaces and Kaldo converters were scrapped in 1978, leaving only the universal mill in operation. The Shotton open hearth furnaces were among the last to operate in Britain until they were closed, together with the blast furnaces, in 1980.

Today (1997), the Shotton works is the principal location within British Steel plc for the production of metallic and paint coated strip, using hot dip and electrolytic methods of galvanising and a roller coater system for paint application. Its six coil to coil coating lines achieved a production of over 1 Mt in 1994–1995 and 1995–1996. The Shelton works is part of British Steel's Sections, Plates and Commercial Steels business. One of the sites that the works originally occupied was cleared and was used for the second National Garden Festival.

### UNITED STEEL COMPANIES LTD

**BY C. BODSWORTH**

The United Steel Companies was formed in 1918 by purchasing the shares of Steel, Peech and Tozer Ltd and Samuel Fox and Co. Ltd, which were located in the vicinity of Sheffield in South Yorkshire. The companies had formed an association in 1917 and had bought the Frodingham Iron and Steel Co. at Scunthorpe which had acquired the Appleby Iron Co. at Scunthorpe in the early 1900s. These works ensured an adequate supply of basic pig iron, and the Workington Iron and Steel Co., which mined hematite ore and coal in Cumberland, was purchased to secure a supply of acid pig iron. The Rothervale collieries were bought to provide a supply of coke and coking coal. Owen and Dyson Ltd and Daniel Doncaster Ltd were assimilated in the 1920s, but the latter firm became independent again in 1937. When it was formed in 1918, the annual ingot making capacity of the company was just over 0.75 Mt. This had increased to over 4 Mt when the company was nationalised in 1967. United Steels had grown to become one of the 100 largest firms in the UK. A history of its formation and organisation has been written by the last Secretary of the company.

The oldest of the original works was S. Fox and Co. Ltd. This was founded in 1842 when Samuel Fox took over an old cotton mill at Stocksbridge to expand his wire drawing activities. He produced wire for crinolines and then, in 1848, began to make the first umbrellas with hollow-section steel frames. This induced him to develop the first cold rolling process for steel. The works started to produce crucible steel and then, in 1862, Bessemer converters were installed, but these were
replaced with open hearth furnaces in 1889. By 1918 the works operated five open hearth furnaces (acid and basic) of 75 tons capacity, billet, bar, rod and rail mills. It was also producing cold rolled strip and railway springs, axles, and tyres.

Steel, Pech and Tozer had been formed as Steel, Pech and Hamilton by the acquisition of the Phoenix Bessemer Steel Co. Ltd and the Ickles bar and rail mills in 1875. Railway tyre and spring shops were added in the 1880s and the Bessemer converters were replaced with small open hearth furnaces. In 1916 the steelmaking capacity of the seven 50 t open hearth furnaces in the Rotherham melting shop were supplemented by the installation of fourteen 80 t furnaces in the Templeborough shop. Both acid and basic practices were operated and the steel was sold as billets, bars and rod, and railway wheels, tyre and axles.

The Frodingham and Appleby works, which were formed in, respectively, 1863 and 1875, had developed blast furnace practices suitable for the extraction of iron from the low grade, calcareous Lincolnshire and the acidic Northamptonshire iron ores. The companies owned the open cast ore workings. The high phosphorus content of the iron produced from these ores was not suitable for the acid Bessemer process, so the production of steel was delayed until a 15 t capacity open hearth furnace was installed in 1890. Other furnaces followed and the first tilting open hearth furnace in Europe, with a capacity of 100 t, was installed in 1901.

Workington Iron and Steel Co. Ltd was formed in 1909. Several works were opened in the mid nineteenth century in West Cumberland to exploit the local deposits of iron ore and coal. The industry prospered when it proved to be the only British source of pig iron suitable for the acid Bessemer process and a strong export market developed in locally produced railway rails. The demand fell sharply, however, with the development of the basic Bessemer process, the import of cheaper iron ores from Spain and increasing competition for the sale of rails. The diminishing profitability led to the amalgamation of the Derwent, Harrington, Lowther, Moss Bay and Solway companies with Workington Hematite Co. Ltd to form Workington Iron and Steel Co. Ltd. (Distington Hematite Co. and the Beckermet ore mines were added when the United Steel Companies was formed.) Production was concentrated on the adjacent Moss Bay and Derwent sites. The main products were railway rails, tyres and axles produced from Bessemer steel, together with pig and foundry iron.

For the first decade of its existence, the United Steel Companies operated as a consortium with the directors exercising mainly financial control and leaving each works to operate under its own management. After the First World War the British iron and steel industry was soon in severe financial difficulties, exacerbated by the colliery strikes in 1921 and 1926, the British return to the Gold Standard in 1925, the policy of free trade, and the subsequent dumping of steel in the UK by overseas competitors. The United Steel Companies survived the recession in better shape than many other companies, but the cost of the expansion of the works, including the formation of Templeborough rolling mills, the construction of new blast furnaces, melting shop and plate mill at Scunthorpe, and modernisation of the Workington works, which had been started shortly after the new company was
formed, resulted in a takeover by City financiers. The share capital was acquired in 1928 by the Austin Friars Trust and the shares were not quoted again on the market until 1935.

One result of this change was the transfer of the head office from Steel, Peech and Tozer to Westbourne Road in Sheffield; a centralised management system was created, removing most of the autonomy from the individual works. Works councils were set up at each plant. Production was rationalised to prevent competition between the works for scarce orders. Henceforth, rails were only produced at Workington, while wheel, tyre and axle production was concentrated at Steel, Peech and Tozer and most of the section rolling was transferred to Scunthorpe.

As the industry emerged from the depression in 1931, the company was in a stronger position than most to embark on a further period of growth. The works most severely affected by the rationalisation was Samuel Fox and it was decided to concentrate the production of alloy steels at Stocksbridge. Two innovative small induction furnaces were installed, followed a few years later by the construction of two 2 t and two 5 t capacity induction furnaces. A rolling mill dedicated to stainless steel production was installed in 1939 and two 12 t arc furnaces were added in 1939–1940. The works became a major supplier of steels destined for products as diverse as motor car and aero engines, ball-bearings and razor blades.

New coke ovens, two 25 t Bessemer converters and a 400 t mixer were installed at Workington. The first two ‘Queens’ blast furnaces were constructed at Scunthorpe in 1939, together with the first Robbins Messiter system ever installed for the blending of iron ores. Two two-pan Greenawalt sinter pans had been built in 1934 and 1936 and two continuous sinter strands were now added to increase production.

A major innovation was the creation of a Central Research Department, adjacent to the Stocksbridge works. Dr Thomas Swinden was appointed as the director and he recruited outstanding talent, including W. E. Bardgett (creep), Dr J. H. Chesters (refractories), Dr A. H. Jay and Dr K. W. Andrews (X-ray) and H. Tremlett (welding). Many important developments in high strength, tough and creep resistant steels emanated from the laboratories, but not always by design. Boron containing steels arose from the chance contamination of an experimental heat with boron from an induction furnace lining. Major improvements were made in the life of refractory linings. The first carbon hearth was installed in one of the Queen blast furnaces in 1942 and a suspended magnesite–chrome roof was built on an open hearth furnace in the Templeborough melting shop in 1947. Dr Swinden died at the end of the Second World War. Under the new director, Dr Frank Saniter, the laboratories expanded further so they were moved to larger premises at Rotherham, where they continue to flourish as the Swinden Technology Centre.

The British steel industry did not expand during the Second World War as rapidly as it had done during the First and relatively few developments occurred in the United Steel Companies. The Stocksbridge works had put down a new plant for the manufacture of leaf springs in 1937 and this was expanded to produce springs for army vehicles. Coil springs were also produced for Oerlikon guns. Steel, Peech and
Tozer put in a plant to forge barrels for small calibre guns and the Scunthorpe works prefabricated Bailey bridges. The only major development was the construction of a steelmaking plant with six electric arc furnaces at Distington Hematite Iron Co. Ltd, adjacent to the Workington works, at the behest of the Government, to produce shell forgings and steel for ball and roller bearings. The Barrow Hematite Iron Co. was also managed on behalf of the Government and was eventually bought by the company.

Changes in welfare arrangements included the opening of medical centres in each of the works. Education officers were appointed and day release courses were started in the works for young employees. Samuel Fox had decreed that any child born in the village of Stocksbridge and who applied to the works on leaving school must be found employment. This pledge was still being honoured over 100 years after the works were founded.

The end of the war found the company in a financially sound position, but with much obsolete plant which required replacement. Government restrictions prohibited major developments and, in 1947, the Company's collieries at Rothervale and in Cumberland were nationalised. The compensation payments were earmarked for developments. Government permission was given for the construction of the Shepcote Lane Rolling Mills, with the purchase of a Sendzimir mill for the rolling of stainless steel sheet, but on the condition that it was a joint development with Firth Vickers Stainless Steels. Permission was also given to build a new Frodingham melting shop in 1947, to reconstruct the section mills there in 1948, and to construct two more Queens blast furnaces in 1950 with expanded sinter production to alleviate a shortage of high grade scrap. This latter development culminated in the perfection of the all sinter charge for blast furnaces. The Appleby-Frodingham Construction Co. was formed to undertake commercial contracts, which included the erection of the radio telescope at Jodrell Bank.

The Barrow Hematite works was converted into an experimental site for the development of the Concast process for continuous casting. When the system had been perfected, the Distington plant was used for the manufacture and sale of continuous casting machines. There was also a short lived diversification into the production of finished goods. The works of Samuel Fox, for example, now began to sell stainless steel tennis rackets and golf clubs.

The iron and steel industry was nationalised in 1951 but was restored to private ownership two years later, and the episode had a negligible effect on the industry. By the mid 1950s LD converters were beginning to replace open hearth furnaces for steelmaking. The technology of this new process was still developing and United Steels sought to defer the high capital cost of conversion until the appropriate plant could be more clearly defined. This was achieved at Appleby-Frodingham by the development of the Ajax process, which facilitated the injection of oxygen into the open hearth furnaces and shortened the duration of the heats. The first furnace was converted in 1958 and by the end of 1960 four furnaces had been converted and a tonnage oxygen plant built. More high grade in house scrap steel could then be transferred to
Steel, Peech and Tozer and the two open hearth melting shops there were replaced by six 140 t electric arc furnaces. Two 135 t arc furnaces were also installed at Samuel Fox.

The Brinsworth medium width strip mill was built at Steel, Peech and Tozer and a new wire mill was built on a greenfield site, near to the Stocksbridge works. Several new departments had been opened at the head office to provide centralised services, ranging from cybernetics to a printing department which produced all the Companies stationery. Consequently, in 1961 it was moved to the Mount in Sheffield, which subsequently became the regional office for British Steel.

Overcapacity in the early 1960s resulted in curtailed orderbooks and restricted production. The company purchased major holdings in a drop stamping manufacturer, Ambrose Shardlows, and a strapping maker, Gerrard Industries, to protect its market, but further plant developments were curtailed.

The British iron and steel industry was nationalised for the second time in 1967. This step marked the demise of the well known company names because, when the industry was returned to private ownership in 1988, many of the works had been closed. But the principal works which had been managed by United Steels continued in full production for several years. The Templeborough works was closed in 1993 and is now finding a new life as the ‘Magna’ industrial museum.

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