It is a great honour to present the Annual Hatfield Lecture, following in the steps of so many illustrious predecessors. The lecture was established in 1944, as a memorial to the late Dr William Hatfield, the renowned Sheffield metallurgist. This lecture is the third in a series on the iron and steel industry and materials science more generally; the others\textsuperscript{1,2} having dealt with the past and present, I shall attempt to look forward, although there is no doubt, to paraphrase Niels Bohr, that prediction is a very imprecise science, especially where it involves the future.

In what will be a very personal view, based on a lifetime's experience in the industry, with United Steel Companies, British Steel and finally Corus, I shall suggest where the foundations of a successful future for steel may lie. The emphasis will be on steel's future, rather than on other materials or competitive threats.

Drivers for change

One question that perplexed me throughout my career concerned the drivers for change: which came first, market demand or technology push? I was certain that no market survey established the requirements or specification of the first wheel or Walkman, although certainly marketing has been responsible for the rapid growth of the latter.

Of the factors affecting demand, important market drivers include:

- the supply–demand balance
- entry cost
- legislation (particularly environmental)
- market needs
- business globalisation
- profit.

A breakdown of world metal consumption illustrates the pre-eminent position of steel. Of the 900 Mt market, carbon steel makes up 810 Mt, stainless steel 31 Mt, primary aluminium 29 Mt, then down through copper, zinc, nickel, and magnesium to titanium at 0.15 Mt. Figure 1 shows demand for steel products to 2000 and a forecast to 2005; overall demand increases steadily but with large geographical differences - marked growth in China and developing Asia, reductions in Central and Eastern Europe, and relative stagnation in Western Europe, the USA, and Japan. Production information shows a very similar trend with strong growth occurring only in the Asia-Pacific regions.

These data illustrate the ongoing issue of surplus capacity from which steel has suffered for some years now. Overall capacity in 2000 amounted to 130 Mt, only China being without a surplus (Fig. 2); Western Europe and the former USSR have significant reductions to make.

The situation in the UK dates back to the 1970s when a steel requirement of some 35 Mt was being predicted; this was followed by the rapid decline in the 1980s and then growth to the present position of 15–17 Mt (Fig. 3). The general decline in UK consuming markets is well known, but this is not the case in all sectors. Figure 4 shows a significant decline in the production of commercial vehicles, but the reduction in volumes of cars from UK manufacturers is offset by recent...
growth as a result of the transplanted plants and, perhaps a little surprisingly, the continuous steady growth of construction -- a topic returned to below.

While steel is usually regarded as a commodity product, growth in commodity products -- steel, soft drinks, book retailing, music (Fig. 5) -- is certainly possible, given the correct marketing strategy and business model: 'There are no commodity products, just tired salesmen.'

It is worth recalling that while the top five automotive companies account for 70% of the global market and the top five for iron ore 90%, the top five steel producers represent only 15%. A snapshot of crude steel production by company in 1999 ranged from USX at 11·3 Mt to Posco at 26·5 Mt and included such examples of consolidation within in the industry as Corus and Thyssen-Krupp, and more will certainly follow. There is a new player being formed, a combination of Usinor, Arbed, and Aceralia, which will have combined sales of £30bn, production of 44 Mt, and employ 110 000 people. The pre-eminent position this company would occupy in the ranks of steel producers is evident: certainly, it would provide an opportunity to establish a dominant position commercially and pursue aggressively business rationalisation, a route that it is familiar to most of us.

To conclude, despite large surplus capacities and stagnant demand (other than in China and South East Asia), growth is possible in mature markets if the correct strategies are adopted. Further concentration of the industry is inevitable.

1 2 World steel production and surplus capacity: 2000

Million tonnes

200
150
100
50
0

Western Europe China Former USSR Japan Rest of Asia USA Lat America Central Europe Row

5 Growth strategies for commodity business

5 Growth strategies for commodity business

Proc. innovation

Over the past 150 years, processes have been invented, continuously developed, and reached maturity until overtaken by new processes (Fig. 6), the electric arc furnace and basic oxygen processes reaching maturity perhaps at the same time and now coming under competition from new processes and combinations that have still to achieve maturity but are certain to bite further into the market. First, however, some thoughts on continuous improvement.

In the classical blast furnace process, coke and sinter are fed into the top of the furnace, hot air is blown in through the tuyeres, and iron exits from the tap hole. Significant improvements have been made in blast furnace performance over the years, and specifically in injecting materials into the furnace. The improvement in productivity achieved and the increases in coal injection rate are shown in Fig. 7. Coal injection has been carried out for many years. The benefits -- reduced fuel costs, improved productivity and stability of operation -- are well known, but the high cost of pulverised fuel systems for preparing the coal made installation prohibitively expensive

6 Process innovation in steelmaking

3 UK steel production 1955-2000

index 1995=100

Commercial Vehicles

Cars

Construction

4 Relative production volumes of metal using industries in the UK

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In some cases, until an innovative engineer and metallurgist at Scunthorpe learnt that a firm in Doncaster had developed a process for injecting coarse coal into boilers. Soon contact was made and the trials began on injecting material into single tuyeres of the blast furnace, soon extending to full furnace operation. Various materials can now be injected including coal and plastics (Fig. 8). The future, though, is even more interesting as far as injection technology is concerned. Perhaps the most significant innovation not been proceeded with to date is the simultaneous injection of granular coal, fine iron ore, and oxygen through the blast furnace tuyeres, by which it is believed to be possible to replace at least 50% of the coke requirement and a considerable portion of the ore input from the sinter plant. The importance of this lies in the high capital cost of integrated plants. If it were feasible to inject such large amounts of coal and ore and avoid some of the costs associated with sinter- and cokemaking the process would have a major impact on steelmaking economics.

Looking at steel production by process route over the past 150 years, the pronounced growth of both oxygen and electric arc steelmaking in recent decades is clear (Fig. 9). New processes are coming to the fore and are predicted to increase in proportion to integrated steelmakers. I believe that this is one area where we have to progress much faster than in the past. These new processes, perhaps not in Europe, but in Asia and other areas of growing demand, will play a major role in the steel industry of the future.

When I joined the industry, steel was produced in open hearth furnaces and by the Ajax process, in which oxygen was injected into the open hearth furnace: we made a lot of steel, and burnt the furnace down occasionally! Ingots were cast, but soon we moved to continuous casting and realised that to provide the caster with steel that was in specification, at temperature, at the right time, the introduction of ladle refining was required. Market demands for purer and purer steels led to more complex process routes being designed to manufacture them. Figure 10 shows an actual process route used to produce steel for transmission of wet acid gases from the North Sea: tapping, gas stirring, reladling to remove any slag, reheating, perhaps some dephosphorisation, powder injection to moderately reduce sulphur and modify the inclusions, followed by vacuum degassing and casting. It is
11 Prototype direct strip caster design

Absolutely wonderful for the metallurgist but unfortunately; it can take about three hours to work through the cycle and can effectively destroy the profit that might be made on such projects.

Looking at the process routes to various products, the electric arc–ladle furnace–caster–rolling mill route is compact and simple, or has the potential to be. Relative to minimills, integrated plants always have to carry high capital baggage—coal and ore blending, sintering, coke making, iron making and steel making facilities—and it is not until the second steelmaking stage is reached that the processes become equivalent. Even then, in most plants occupying ground traditionally held by big steel, the continuous casting, slab reheating, and rolling processes are discrete and in different parts of the works.

These high cost routes provided a major driver for innovation to reduce capital and operating costs and to resize to plants capable of working in small regional markets. This was achieved by collapsing the process route, for example by the continuous casting of shapes as close in dimension to the final product as possible, i.e. near net shape casting, to avoid primary rolling costs. A good example of this is beam blanks, a well known technology available to all. Another example, thin slab casting, can permit the linking of the casting machine and rolling mill. Long cast slabs are processed through equalising furnaces, making use of the energy contained within the solidified strand, through roughing and finishing mills and cooling beds, before coiling, often continuously as far as is practicable. The approach is equally applicable to hot strip, bar, and shape products. Figure 11 should look familiar, Shown by Frank Fitzgerald in 1990 and Jeff Edington in 1995, it illustrates the strip casting process under development at the Grangetown Laboratories on Teeside. Figure 12 shows how the dream has become reality with the introduction of some inline reduction and cooling and a double coiling system. In fact such a plant was described at a recent SMEA lecture by Gerald Hochenblicher of VAI.

BuroStrip, in which VAI is a partner, claims to be casting carbon steels and stainless successfully at speeds up to 150 m min⁻¹. Thicknesses of 1.5–3.5 mm are scheduled for production in plants of capacity up to 0.5 Mt/year.

These developments have led to significant cost reductions in the capital associated with steel products production and Fig. 13 shows a capital cost comparison between a single integrated works scheduled to produce 4 Mt/year and that associated with two minimill plants also producing 4 Mt but using 25% briquetted reduced iron (BRI). Avoidance of the cost of BRI leads to the inevitable conclusion that further significant reductions in capital are possible. However, the product must be fit for the market place, and while minimills certainly have had major successes and rapidly replaced traditional steelmaking in the production of many commercial products, they still have some way to go in terms of large structural sections, heavy plates, special wire rod, and strip grades. Some of these may always be the province of the integrated manufacturers.

In summary, the primary process has survived so far by innovating and reacting to competitive threats. The complexity of the process routes in high productivity, multiproduct plants severely limits their potential to operate at minimum cost. I do not believe further new integrated plants will ever be built in the developed countries. The most likely economic solution is for a policy of ‘make do and mend’ as the industry is rationalised further, while new investment will be concentrated in many compact plants. These may come to play a part in steelmaking in Europe, but certainly will continue to do so with a vengeance in the Far East.

12 Production direct strip caster layout

13 Cost comparison of single integrated plant and two minimills, both producing 4 Mt/year of steel

**Product innovations**

Here I would like to describe some examples in heavy plate, heavy sections and wire rod.

An important driver in the post-war effort to produce tough steels was the experience with the Liberty Ships built in the USA during the Second World War, which graphically illustrated the need to match the quality of the product, the process route, and design considerations. The Liberty Ships were designed for riveting. The steel was brittle yet the ships were welded together. The combination of very high operating stresses, workmanship that left much to be desired and unfamiliarity with the welding process resulted in ships breaking apart, often before they were launched.
14 Microstructure control of rolled products by thermomechanical controlled processing

Much progress has since been made in the production of strong, tough, weldable steels through control of chemistry and microstructure and Fig. 14 illustrates the opportunities for controlling the structure by thermomechanical controlled processing (TMCP): reheating the steel slabs to various temperatures, rolling in the recrystallisation range, holding until the temperature reaches the range where no recrystallisation occurs, and rolling further to give a deformed austenite microstructure, which can then be allowed to cool normally in the 'classic' hot rolling (HR) process route, transforming to fine grained ferrite plus pearlite. Accelerating the cooling rate in water treatment plants (ACC) gives fine ferrite plus bainite, or in the case of direct quenching (DQ) ferrite plus martensite, which can be tempered to generate the required properties. These developments led to significant improvements in both strength and toughness. Figure 15 illustrates the implications as far as strength is concerned: note the marked reduction in carbon equivalent value that can be achieved in developing plate of the same strength using thermomechanical processing as opposed to heat treatment.

There is little doubt that without development of these processes, exploration, extraction, and transmission of gas from the North Sea would have been considerably delayed.

Figure 16 shows some of the vast range of products from the large structural mill at Teesside, from the small column to the lower left beam which weighs >1 t m⁻¹ to the beam on the right which is actually a metre in depth. In this mill the cast slab is vertically rolled, and then edge rolled with a combination of horizontal rolling to get the final shape. The prime target of section mills has always been to obtain correct product shape with the maximum yield. Gradually this requirement is being integrated with the metallurgical requirements, a process in which mathematical modelling is playing an increasingly important role. Linking these models with those related to the development of the microstructure of the steel proves extremely exciting. As the bar is deformed in the rolling process, it is possible to predict how the initial microstructure formed during reheating changes during dynamic recrystallisation in the roll gap, static recrystallisation, and grain growth. The industry is now beginning to bring together the two technologies and by putting a finite element mesh on the models of the slab rolling process discussed above (Fig. 17), it is possible to predict the distributions of temperature and deformation throughout the rolling process, produce plots of the equivalent plastic strain across the section, and link this to the microstructural developments that occur – allowing development of new products much faster than in the past.

One example of this is the asymmetric beam: it is difficult to roll sections that are asymmetric for a number of reasons and I believe that the beam shown in Fig. 18 is the first asymmetric section rolled in routine production operations. - However, as well as allowing rapid development of completely new products, model driven development also speeds reaction to the marketplace, making changes to the dimensions of existing products possible very quickly.

Turning to wire and rod products, understanding the relationship between rod and wire properties and the influence of processing on these has led again to the development of sophisticated mathematical models to simulate a single slug of wire passing through guides and dies in the wire drawing process; accurate prediction of the high strains achieved at the throat of the die is particularly important. This has permitted development of total wire drawing models that make it possible to understand what goes on in the wire drawing
17 Prediction of temperature and deformation during rolling

A good example of the impact of continuous development of wire strength is that of suspension bridges, which are an important market for high carbon steel wire ropes; 2 or 3 mm diameter hard drawn high carbon wires are formed into ropes and subsequently into cables to form part of the suspension rig itself. The development of wire strength has been fundamental to the increased span of suspension bridges (Fig.19), from the Brooklyn Bridge in the 1980s with wires of 1100 MPa strength to the Golden Gate Bridge (1280 m span, wire strength 1520 MPa), and the Humber Bridge (1410 m, 1560 MPa). A significant hike then occurred to the Akashi Kaikyo Bridge (1991 m, 1770 MPa); this phenomenal increase in strength certainly made a suspension bridge more attractive to build by changing the design from a four rope to a two rope bridge with consequent reductions in costs, material weights, and foundations. The Strait of Messina Bridge (3300 m span), not yet a firm project, will join Sicily to mainland Italy and will contain 166 000 t of steel in the cables.

In conclusion, the benefits of mathematical modelling of the production and metallurgical processes cannot be overstated. Detailed knowledge of the market will allow these models to be applied to satisfy the market needs. Focused, systematic innovation will enable faster development of better products and enable far faster inroads into the marketplace. It is possible to predict with confidence that thermomechanical processing will grow in importance in all process sectors.

18 World's first asymmetric beam rolled in routine production

19 Development of strength in steel wires for suspension bridge construction

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Innovation in application

In 1981, a British Steel study into the costs of fire protection in buildings concluded that the cost of insulating fibre and insulating boards for protecting structural steelwork in multistorey buildings amounted to 31% of the cost of the building, more than the cost of the steel; this was certainly the major reason why steel could make no inroad into the market for concrete.

The reaction was to undertake a series of tests at the Fire Research Centre at Cardington in which fires were carefully
set in, for example, a four storey building, fully instrumented to obtain the maximum information on the rate of heat transfer to the steel and the effect on stress and strain loading. This work led to very significant reductions in the quantity and cost of fire protection required and very significant changes in the designs codes for steel, bringing advantages for steel over concrete. Adjusting the 1981 cost of structural steelwork of £985/t to its equivalent 2000 value of £2400/t, Fig. 20 shows that the total cost has been reduced by 55%, fire protection costs by 64%, and the steel cost by 42% in real terms. The beneficial effects in the UK marketplace have been marked, with steel's market share rising from 33 to 67% between 1980 and 2000, while concrete declined from 52 to 20%. However, there is much to be done to achieve similar levels of penetration in mainland Europe, where steel usage ranges from 30% in Spain and The Netherlands to as low as 10% in Italy.

Another application of interest is Corus Bi-Steel, which consists of two plates connected by friction welded bars (Fig. 21), filled with concrete to improve the properties. Bi-Steel has excellent impact strength and behaves in a semiductile manor. One major application for this product is in blast protection structures; another is in seismic applications, which has received much interest following the earthquakes in Chiba in Japan and North Ridge in Los Angeles.

These earthquakes resulted in a major, international work programme covering design, materials, fabrication and in-service stress patterns during seismic events. Figure 22 depicts schematically how failures were generally concentrated in the junction areas in the corners of the steel structures. Any fractures propagated down the weld metal and subsequently in the base material parallel to the weld, with some cracking through the material on occasions. However, the major concern was lamellar tearing, which always occurred in the base metal, always outside the visible heat affected zone, and generally parallel to the weld fusion boundaries. These issues led to a major development programme examining the effect of steel chemistry, cleanness, segregation, and rolling on toughness and susceptibility to lamellar tearing. The output of this work was a series of beams and columns with improved properties, and quite a large rig was constructed to test these materials, 19 m in width and 9 m high. The beam-column connections were welded with very high levels of restraint and hydraulically jacked to preset levels, examined, then rejoaked to failure: no connection failures occurred, failure being by buckling of the section itself, a very satisfactory outcome. Steels having significantly better ability to withstand the rigours of seismic events have been developed, but, as with the Liberty Ships, the real requirement is to get the welding processes correct – the weld metals in the failed structures did not possess adequate toughness, design of connections left something to be desired, and workmanship was a key area responsible for the failures. Perhaps the most important conclusion as far as steel is concerned in respect to both North Ridge and Chiba is that in neither of those failures was there any loss of life in a steel framed building.

Laser cutting and welding of thin gauge materials, for example in light goods and automotive applications, has been common practice for some time. More recently, ship builders and earth moving equipment manufacturers have become interested in laser processing for heavier gauge material.
Corus has constructed a heavy product laser processing facility with a 25 kW CO₂ laser bank, transmitted by optical fibres along a gantry to a laser head, which is manipulated by a five axis robot. The objective of this work was to develop expertise in laser cutting and welding of heavy gauge products and specifically to ensure that products were available that would meet any new requirements/demands coming from the market place. to build a competitive edge and to develop better, more exciting products. Submerged arc and laser weld cross-sections are compared in Fig. 23. The submerged arc weld has a large fusion zone with the heat affected zone extending beyond the extremities of the photograph, whereas the laser weld, which uses no filler material, fuses the two parts together with almost no heat affected zone. This is reflected in the two main advantages of laser processing: minimal or no distortion and reduced cost owing to the lack of expenditure on the welding electrodes. The opportunities examined included butt welding of wide plates or bespoke sections, stake welding to form sections, T joints, perhaps of different materials, and cladding of high performance materials onto low cost base material. Although higher capital costs are incurred compared with the conventional routes, laser welding has the capability to make products that are impossible by other processes.

The final example concerns knowledge based construction. Egan characterised construction industry performance in the UK as one of fragmentation and low margins, inefficiency, waste, and cost and time overruns being common with little learning and innovation. This all leads, as might be expected, to pronounced client dissatisfaction. Egan pointed out the potential of information and communications technology as a key enabler in the necessary improvement of the construction industry, to bring together design of buildings and components:

New technologies have proved very useful in the design of buildings and their components, and in the exchange of design information throughout the construction team. There are enormous benefits to be gained, in terms of eliminating waste and rework for example, from using modern CAD technology to prototype buildings and by rapidly exchanging information on design changes. This led Corus to launch the Knowledge Based Construction project, the vision of which was to enable an architect, client, and consulting engineers to design and modify proposed constructions very fast, test and cost concepts rapidly, construct buildings on screen, in two and three dimensions, and to support the designs with product libraries which describe the characteristics, availability, and costs of all the products available. To be able to redesign structures rapidly, for example to reposition lift shafts, where the technology promises the capability to allow automatic redesign of the structure to cope with the basic change in design via the use of 'intelligent objects'. And finally to provide a platform where all the associated data and knowledge could be shared in real time between those involved.

A typical construction sequence would begin with the boundaries of the site being defined with security fencing; piling being driven for retaining walls, containment, or for basement structures; bearing piles being introduced as necessary; perhaps for high rise buildings, the concrete pad; the structure secured to foundations with anchor bolts, structural steel work installed; floor decking being input to the asymmetric beam mentioned above; reinforcing materials, rebar, remesh, the concrete being laid. The objective is to get the secondary steelwork and the roofing in position as rapidly as possible to ensure the building is watertight as early as possible in the process, for rapid completion. All sorts of options are available for wall materials, decorative and roofing materials – different colours, different textures for the claddings. The system that the project envisaged would allow a building to be designed on a laptop computer between people talking, then converted into a two-dimensional drawing for people in the field to work on. It is absolutely vital that this work is continued to maintain and extend the dominant position of steel in construction.

Conclusions
In drawing overall conclusions, it is important to emphasise again the difficulty of predicting the future: the one thing I soon learnt about forecasts was that they were never right. The future may be possible to predict if you are talking about tomorrow but accurate long term predictions are impossible.

Nevertheless, I would suggest that the successful steelmaker of the future would have to give serious consideration to the following points:

- continuous innovation – of process, product, and application technology – will be fundamental to the survival of the steel industry
construction continues to provide the major opportunities for both UK and world steel. Innovative applications for standard products will show significant benefits, compared with the past emphasis on development of new products. Solutions must be brought to market faster to maximise early benefits. Knowledge is the source of competitive edge: we have to move from simply selling bars of steel to encapsulating our knowledge of the product and its effective use and ensuring we achieve adequate value from the market place.

However in striving to achieve success in new applications and products, we must remember to keep hold of existing processes. Remember that the past actually did exist: the future exists only as a place we are going to. The secret of success is to remember and learn from the past, live the present, and create the future.

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References

Dr Mike Pettifor retired last year as Director, Technical of Corus CG&I. He is Chairman of the Steel Division of the Institute of Materials, Minerals and Mining and can be contacted through the SW editorial office.

British Steel Research Achievements 1970–90
A monograph by P. H. Scholes with a foreword by Dr F. Fitzgerald

The period 1970–1990 was a time of rapid technological change in the British Steel Corporation. It was underpinned by intensive research and development to ensure the success of new technologies, and to build a profitable industry. This monograph describes some of the research achievements during this period, based largely on articles published in Steelresearch. It is no sense comprehensive but rather the intention has been to illustrate the breadth and scope of activities across a broad spectrum of technology.

Following nationalisation of most of the steel industry in 1967, there was a pressing need to restructure research facilities. In 1970 there were more than 20 disparate research establishments widely dispersed throughout the UK. Restructuring took place in three stages. The outcome was an efficient organisation able to provide technical support for the operating works and businesses. The basic structure and major facilities of Corporate R&D remained in place after privatisation in 1988 until British Steel plc merged in 1999 with Hoogovens BV. The former research laboratories are now part of Corus RD&T.

Selected topics are presented in three sections:
- process research
- product research
- environmental research.

The CD contains PDF files of the monograph optimised for printing and for reading on the screen, together with a fully searchable bibliography of references to papers published in the technical literature.

Copies of the disk are available from the author, priced £5 (~10) including P&P. Contact: phscholes@lineone.net.