THE DEVELOPMENT OF THE EARLY STEELMAKING PROCESSES - AN ESSAY IN THE HISTORY OF TECHNOLOGY

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9 THE CHANGING SCENE: THE NEED FOR MORE STEEL

> 'During the 1850s some Sheffield crucible steelmakers began to count their capital in £100,000s ... while in the 1860s a few rose into the millionaire class, but the difficulties of forming larger products from crucible steel were considerable, though the greater reliability of that material compared with the ordinary Bessemer steel enabled it to hold its own for a decade or more .... By then, Bessemer was beginning to make inroads even in Sheffield, and soon Siemens open hearth process arrived also, with its firmer reputation for reliability. Yet until the coming of the electric furnaces in the twentieth century the small crucible and shear steelmakers were not greatly affected by the new processes'.
>
> J. C. Carr (1960)

I The Background

From previous indications, particularly with reference to possible variants of the crucible process, it will have become obvious that steel may be produced by combining the required amount of carbon with iron by other methods in addition to the traditional Continental finery processes and the cementation and crucible methods which have formed the burden of the discussion to this point.

For these alternative methods to be viable, however, they had to satisfy a need and be competitive with the existing processes. This combination is a complex one and the conditions varied at different periods. In times of shortage of raw materials, as in the Napoleonic Wars when essential supplies of Swedish iron were partly cut off in this country, an alternative supply of steel would be welcomed, and somewhat less importance placed on its absolute quality; it is suggested that the investigation of Mushet's steel by Peter Stubs to supplement his dwindling supplies from Sheffield around 1800 was due to this cause.[1] Alternatively, in the expansion of engineering in the period from 1850 to 1880,[2] the need for a stronger material than wrought iron, but at a price which was more reasonable than that of crucible steel, and in piece sizes in which crucible steel was not readily available, brought forth the evaluation of a large number of alternative routes, only a small proportion of which were really practical and very few of which produced any real quantities of commercial steel. The two well known processes which won through, those of Bessemer and of Siemens, laid the foundation for the bulk

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1 T. S. Ashton, An Eighteenth Century Industrialist (Manchester, 1939), pp.49-50.

2 This was something of a golden age in steel technology here in Britain. Many famous names can be recalled: Dr. Percy wrote the first comprehensive text book on iron and steel in 1864; Lowthian Bell, William Fairburn, Windsor Richards, George Snelus, William Menelaus and other patriarchal figures were active in the iron and steel works; The Iron and Steel Institute was founded in 1869; William Siemens, George Parry, Robert Mushet and Henry Bessemer were notable in the field of invention and Gilchrist Thomas put the final seal on all this when he perfected the basic processes to deal with the phosphorus problem.

steel production over the next hundred years.

In 1850, steel production in this country, which at that time led the world, was probably not more than 50,000 tons per annum, whilst the complementary production of wrought iron was of the order of two million tons. The price differential was large, steel selling at £50 to £60 per ton whilst wrought iron was available at £10 to £15 per ton. For cutting tools, files, cutlery, surgical instruments and razors crucible steel was essential, but for general applications in engineering, and particularly for rails, springs and buffers and the tyres for locomotive and waggon wheels for the railways, there was this urgent need for a stronger material than wrought iron for which some modest increase in price could be accepted. The crucible process, however, could not be expected to meet this requirement , either from the standpoint of economics or of production capacity. It was this situation which intensified the search for alternative methods. Many of the proposed processes had little hope of long term success and some, which originally appeared to have a bright future, had a place only for a short time and then vanished. Even the successful ones had long gestation periods. It was in 1856 that Bessemer read his famous paper at the Cheltenham meeting of the British Association, but it was not until 1861-62 that the process was becoming firmly established. Similarly, the Open Hearth process, which was really initiated by work in France in 1864, Siemens' own patents dating from 1867, was producing only some 70,000 tons of steel per annum by 1873 - less than was produced by the cementation and crucible processes in Sheffield at that time; Bessemer production had, by this stage, achieved about half a million tons per annum but it should be noted that the production of wrought iron was then nearing three million tons in the year.

A study of the patent applications gives some idea of the activity devoted to steelmaking development. Taking the twenty year period of 1853 to 1873, the mean rate of increase in the number of applications in total was about 2.5% per annum, whilst specifically in the field of cast and wrought iron technology it was double this, which would appear to indicate the growing importance of the engineering industries. With regard to steel, however, the trend is markedly different, as can be demonstrated by reference to Figure 28. This clearly shows two activity peaks, around 1857 and 1867 respectively, due, in the main, to the Bessemer and to the Siemens inventions. If the patent applications related to these two are discounted, however, there is still a steep rise from 1853 to 1857 and a continued activity for a further decade. The study of such developments on a purely chronological basis is simply confusing, due to the variety of technological approaches to the common end; the most reasonable approach is, in fact, to consider the situation from the standpoint of the technological basis involved.

II Methods Involving the Direct Reduction of Iron Ore

These are what in a previous context would have been termed 'Direct Processes', of which the production of steel in the bloomery furnace was a prime example. The earliest of these newer processes recorded was that of Edward Lucas in 1791.[1] Operating on Lancashire or Cumberland haematite, he used a variant of the cementation process, but stratifying the pieces of ore, rather than bars of iron, with the charcoal.

> 'When this operation is ended the ore thus cemented may be taken out and will be found to be converted to a metal, intermixed with the immetallic earth of the ore and adhering together in large masses. If the process has been well conducted and the ore good the greatest part will be found to be steel and sufficiently converted for making into cast steel and may be run into ingots for that purpose'.

This, then was not entirely a primary process, but it combined the steps usually covered by the blast furnace, the finery and

1 British Patent No. 1869, 18th April 1792. This patent, incidentally, refers to charcoal as 'yielding the inflammable principle or what is called by some chymists phlogiston'.

the cementation process. It derived from an establishment at Dronfield, near Sheffield, which was eventually to use a modification of the cementation process for the partial decarburisation of cast iron, to provide the so-called 'malleable iron castings'; indeed, this in itself could be looked upon as a rather special case of steelmaking since the final article usually contained between 0.5% and 1.0% of carbon.[1] This is an interesting example of providing the desired result, a cast shape with most of the characteristics of steel, at a time when the difficulties of casting steel itself into complicated moulds was not yet capable of solution. David Mushet put these difficulties in his own words :[2]

> 'Cast steel is too volatile when in fusion to admit of being run into any shape except straight moulds of a considerable diameter'

and the commercial production of steel castings was not to

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1 British Patent No. 2767, Samuel Lucas, 30th May 1804. The original patent covered the heating of articles of cast iron in powdered iron ore; this could be arranged in layers in the chests of a steel converting furnace, with intervening layers of sand to prevent adhesion.

2 British Patent No. 2447, David Mushet, 13th November 1800. This patent has already been quoted as specifying a method of producing crucible steel from wrought iron and charcoal, which appears to have been the more important feature of the patent. It also describes a method for the production of coke, as well as a variant of the 'malleablising' process to be patented by Lucas some four years later, aimed at giving his crucible steel a skin of low carbon material so that it could be more readily forge welded 'but without the usual blisters or flaws'.

be achieved for another fifty years.

Mushet himself aimed to obtain a truly direct process, based on the crucible furnace :[1]

> '.... when I meet with or procure iron stones or iron ores sufficiently rich and free from foreign mixtures I save the time and expence necessary for the conversion of such iron stone or iron ore, first into cast and pig iron and afterwards, by a tedious and expensive process, accompanied by a great waste of material into bar iron. For such ore or iron stone, being previously roasted or torrified, when that process may be found necessary, which will often happen, may be substituted for the bar iron, scrap or waste iron as before described, and the result will be cast steel, if a proper quantity of charcoal, charcoal dust, pit coal, pit coal dust, plumbago or black lead or of any substance or things containing carbonaceous matter has been used'.

The patent obtained by Hawkins in 1836[2] does not seem to offer anything new, being in essence the Lucas method working on mixtures of :

> 'burnt mine (roasted iron ore, in other words) broken into lumps of 3 lb. to 4 lb. in weight and each lump imbedded in powdered charcoal and subjected to high temperatures in pots for .... eighty hours .... or seventy six hours or seventy two hours'.

His 'pots' were either ordinary crucibles or cast iron pots or :

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1 British Patent No. 2447, David Mushet, 13th November 1800.

2 British Patent No. 7142, John Isaac Hawkins, 4th July 1836.

> '.... in carrying the improvement into effect on the large scale, I use the ordinary steel converting furnaces and proceed as nearly as possible in charging them and firing them as I did with the testing samples ....'.

He also pointed out that the product could be :

> 'by the simple and well known process of casting, converted into .... cast steel'.

A rather curious combination of the cementation process, for converting bar iron to steel, and the direct reduction of iron ore, was patented in 1854 by another Samuel Lucas, who seems to have been the grandson of the earlier one.[1] He placed bars of iron and layers of iron ore, separated from each other by charcoal and with some admixture of oxide of manganese. With sufficient charcoal it appeared that the lumps of ore could be taken out, reheated and forged to bars of steel; otherwise, they, and the iron bars, could be broken up and melted in crucibles to produce ingots.

Still another variant on the same theme, but a little more sophisticated, came two years later.[2] The ore, either oxide or carbonate, was roasted and crushed and then subjected to a magnetic separation process for removal of some of the impurities. The product, mixed with fluxes if necessary, was placed in layers in a cementation furnace chest with alternate layers of charcoal. The charge was then taken to white heat and kept there for about 48 hours

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1 British Patent No. 1730, 7th August 1854.

2 British Patent No. 851, William Edward Newton, 8th April 1856.

and allowed to cool. The resulting mixture was crushed and again magnetically separated and the magnetic portion melted in crucibles and cast into ingots, as usual.

Whether any of these processes were applied on any real scale is difficult to establish but it seems quite evident that there was continuing activity of this kind at the Lucas establishment. There is, however, a rather telling comment by Dr. John Percy :[1]

> 'Experiments on the direct production of cast steel from iron ores in crucibles were made by Mr. E. Riley at the Dowlais Ironworks a few years ago. Excellent steel for chisels, etc., of which I have seen specimens, was occasionally obtained; but it was not found possible to ensure uniform results'.

There was also considerable activity, from about 1845 onwards, in the production of a reduced iron product from iron ore, which could subsequently be utilised in steelmaking. This differed essentially from the blast furnace smelting procedure, in that the reduction took place in the solid state, the product being what was eventually known as 'sponge iron'.[2]

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1 J. Percy, Metallurgy: Iron and Steel (London, 1864), p.765.

2 This is one of those examples of a concept being worked on at a time when the facilities required were not really available. After discarding the idea eventually as unworkable, it was then picked up again about a hundred years later and a variant of the process now supplies major quantities of iron for today's modern steelmaking plants around the world. It is more economical to transport the iron after removal of the impurities in the ore as well as the oxygen combined with the iron; the 'gangue' in the iron ore is useless ballast.

The first reference to such a process is in a patent taken out by Adrien Chenot in 1846,[1] at a time when he had already spent ten years of research into the project. Two further patents were taken out in 1854 and a further four some two years later,[2] whilst a lengthy French text appeared in 1859, describing the process and its applications.[3] The final summary, which contains some interesting comments on the contemporary scene, may be translated as follows :

> 'Messrs. Bessemer, Uchatius and Tessié de Motay have very seriously occupied public attention and perhaps the last word has not yet been heard from them. The Bessemer Process, however has, for good reason, been abandoned. Based on a most violent combustion of the carbon contained in molten cast iron, it burned too great a proportion of the iron produced. Taylor has most ingeniously modified the apparatus to make the process almost continuous but the practical trials throughout have not been at all satisfactory. Uchatius has obtained steel by decarburising charcoal cast iron, preferably granulated, using oxide of iron with a little manganese, the mixture being melted in ordinary crucibles. The product has left something to be desired but, nevertheless, has been usable. The procedure of Tessié de Motay at Fontaine, based on sound chemical principles, has given good results but the manipulative technique is delicate and complex and it does not seem that it can replace the production of steel by puddling which, as carried out at Seraing, at

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1 British Patent No. 11515, 31st December 1846.

2 British Patents Nos. 246, 1st February 1854, and 658, 20th March 1854, both in the name of Claude Adrien Bernard Chenot. British Patents Nos. 1587 to 1590, 7th July 1856, in the joint names of Alfred Louis Stanislas Chenot and Eugene Charles Adrien Chenot.

3 E. Grateau, 'Mémoire sur la Fabrication de l'Acier Fondu per le Procédé Chenot', Revue Universelle (1859), vol.6, pp.1-62.

Creusot and so on, is much simpler and surer. Chenot's process, however, the fruit of some twenty five years of perseverent research, and using truly industrial principles, presents the happiest alliance of science and practice and it will remain as an accomplished fact in metallurgy, which has had its horizon broadened by giving to industry a new means of obtaining common steel of good quality whose use is expanding markedly with each day that passes'.

History was, of course, to prove the author wrong.[1] Chenot's method for the production of sponge iron was a complicated one and details may be found elsewhere.[2] Having obtained his reduced iron, his preferred method of converting this into steel was to mix it with the appropriate amount of carbonaceous matter, generally charcoal, together with a small amount of manganese and, if necessary, some resin binder, to compress the mixture into small blocks, and then to remelt the blocks in a crucible to produce ingots in the ordinary manner. Chenot claimed that steel made in this manner was equal to that made by 'the house of Huntsman' and figures are quoted[3] for the

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1 This was written, of course, at the time when the Bessemer process was in considerable disrepute. The original successes had been overshadowed by widespread failures on a commercial scale, quite baffling to Bessemer, but soon to be recognised as being caused by the high phosphorus contents of the majority of British cast irons. Taylor's modifications, consisting of throwing the molten cast iron in a thin stream by centrifugal action to assist in the oxidation of the carbon (British Patent No. 627, 3rd March 1857) never seem to have been seriously applied. The Uchatius process has already been described (see Chapter 8). Puddled steel was temporarily quite important, as will be discussed shortly. The only reference which can be found to Tessié de Motay is in British Patent No. 535, 1st March 1856, where a modification of the puddling process for producing steel is described.

2 Information on the process collected from the various patents and the paper by Grateau noted above can be found in Appendix RR.

3 Grateau, loc.cit., pp.56-57 and attached table.

costs of production of forged bars in cast steel which indicate a very similar figure to that quoted by le Play for Sheffield practice, some seventeen years earlier, via the cementation process and crucible furnace route.[1] It seems that the Sheffield firm of Moss and Gamble tried out the Chenot process in 1864 to 1865. This does not seem to have been a success and it would seem that, due to the bulk of the compressed blocks, compared with the normal metallic charges, the volume of liquid steel in the crucible had to be lowered, with some adverse effect on the economics.[2]

Although the Chenot process does not seem to have had the predicted success, with the coming of the Open Heath process there appeared to be a real market for sponge iron and efforts were made to improve the process. George Snelus, one of the most eminent of the British works metallurgists of the time, suggested a vertical circular retort.[3] In the proposed method, the powdered ore was fed to a hopper at the top of the furnace from which it passed in a steady trickle through a heated column of reducing gas, before being collected in a chamber filled with spent gas to prevent

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1 F. le Play, 'Mémoire sur la Fabrication de l'Acier en Yorkshire', Annales des Mines, 4me. Serie, Tome III (1843), p.668.

2 J. S. Jeans, Steel: Its History .... (London, 1880), p.41. He comments, however, that Fairburn visited the French works of Bageney et Cie., and did not hesitate to declare that a superior quality of steel was thereby obtained.

3 British Patent No. 616, 20th August 1869.

reoxidation. There is no firm evidence for the use of Snelus's furnace. The efforts made to improve on Chenot, however, were numerous. Blair, in America, spent almost ten years, first with a horizontal retort and then with a vertical retort, eventually using a lime addition and handling up to 200 tons of ore per week in a single 36 foot high furnace.[1] In fact, over the years from 1855 to 1880 the patent literature contains numerous examples of processes of this type.[2]

What is not usually appreciated, however, is that the bulk of the effort made by Siemens, at the time he was developing his Open Hearth furnace, was in the search for a direct steelmaking process based on the pre-reduction of the ore prior to converting the sponge to steel. He made

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1 H. M. Howe, The Metallurgy of Steel (New York, 1891), pp.278-280.

2 Isaac Rogers proposed a rotating cylindrical furnace along which a mixture of ore and charcoal was driven by a screw, the reduced product passing into a reverberatory hearth for conversion to steel (British Patents Nos. 629, 20th March 1855 and 262, 31st January 1861); Frederick Gurlt had a shaft type furnace, producer gas fired, in which the gas composition was controlled so as to be carburising (British Patent No. 1679, 16th July 1856) and it is interesting to note that this process was in operation in Bilbao as late as 1884 (Howe, loc.cit., p.275); a patent taken out by Bonneville on behalf of J. Absterdam somewhat later used a coal fired retort containing a mixture of ore and carbonaceous matter, hydrocarbon oil being introduced during the process into the retort and the gases taken off as 'illuminating gas', the retort subsequently being allowed to go quite cold before taking out the reduced ore (British Patent No. 186, 6th July 1869). These are the most interesting of many applications.

two designs to this end, one using a vertical reduction retort above the Open Hearth and the other using a horizontal rotating retort for feeding the furnace. The earlier design[1] had a pair of vertical cast iron retorts above the working area of the steelmaking furnace, with a space around each retort heated by the flame from the furnace itself. About 28 lb. of charcoal was charged through each retort hopper and then the rest of the space filled with ore. Producer gas was injected through pipes in the centres of the hoppers and this deoxidised the ore which had been heated to redness. About half a ton of pig iron had meanwhile been charged into the furnace; on melting, it began to dissolve the bottom end of the column of reduced iron ore. Regular feeding of ore through the top of the hoppers would continue for three or four hours; feeding would then cease and a clay coated cast iron plate, suspended on wires, would be placed on top of the remaining charge, sinking with the charge and eventually sealing the mouth to the retort, so that the next charge could begin to be filled into the retort. Meanwhile the contents of the furnace would be brought to the desired composition, spiegeleisen also being added, and the metal tapped. Later comment on this process should be quoted :[2]

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1 British Patent No. 2395, (1867), final specification 18th February 1868.

2 Howe, <u>loc.cit.</u>, p.283.

> 'Today we wonder that a man of Siemens' genius and judgement could have seriously entertained so crude a project even twenty one years ago. To maintain these hoppers, exposed thus in an open hearth furnace, to heat these thick bodies of ore through and to deoxidise them at the necessarily low temperature in any reasonable time, to keep the open hearth furnace waiting while the charge of ore was descending - well, well! Today's folly is wiser than yesterday's wisdom'.

These words are really a little harsh. In 1867 bulk steelmaking was still in its infancy. By the time Howe wrote his comments, the basic steelmaking processes had given phenomenal growth to world steelmaking and the Open Hearth furnace, by then rapidly overtaking the Bessemer process as the leading method of steel production, was surely sufficient tribute to Siemens' genius, apart from the use of his regenerative furnace in crucible steelmaking, in the glass industry and elsewhere. Moreover, Siemens had a clear grasp of the principles involved, even if he was over-ambitious in some of his engineering. Indeed, his second version of a direct steelmaking process[1] is a most elegant conception and, since it predated the currently accepted versions of such processes by almost a hundred years, is worthy of comment; it consisted of a rotary reducing furnace feeding an open hearth furnace. That it worked

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1 British Patent No. 1892, 10th June 1868. Details of the process taken from the patent specification may be consulted in Appendix SS.

there seems no doubt.[1] In the event, improvements in the blast furnace economy and the growing availability of steel and iron scrap combined to make the direct process an unnecessary complication and the 'Open Hearth' process took over.

The direct steelmaking processes and the production of a reduced iron product from iron ore, other than the conventional use of the blast furnace, did not, therefore, at this period of time have any great impact on the steel making scene; that they were ever conceived, however, is indicative both of the growing appreciation of steelmaking technology and of the increasing need for steel.

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1 The works set up by Charles Tennant at Hallside near Glasgow were originally intended to utilise the 'Blue Billy' or iron oxide remaining from the use of iron pyrites, as a source of sulphur for Tennant's chemical works. In true economic exploitation, the residue after ignition (which released the sulphur as sulphur dioxide for subsequent conversion to sulphuric acid) was treated to recover the copper it contained. The balance was the 'Blue Billy' and Charles Siemens examined the situation and recommended his new process. Furnaces were installed, in accordance with the 1868 patent, and some of the iron oxide waste was used; the furnaces, however, worked very well on the pig and scrap process, and eventually it was found more convenient and more economical to utilise further furnaces of the conventional type. This plant was to produce Open Hearth steel for just over a hundred years.

III Methods Involving the Partial Decarburisation of Cast Iron without the Production of Molten Steel

Methods of this type had been in use on the Continent since the invention of the blast furnace and have already been discussed. The nineteenth century, however, brought together the older ideas and the current method for producing wrought iron; the outcome was the production of puddled steel which was a most important addition to the ranks of steelmaking methods in the latter half of the century.[1]

The puddling furnace was invented by Henry Cort, in 1784,[2] and the process was modified significantly during the early years of the nineteenth century into the form which continued, virtually unchanged, for over a hundred years, indeed, until the production of wrought iron ceased within the last twenty years. The process has been described in great detail on several occasions[3] and Figure 29 indicates

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1 The account which follows is an extended version of two papers published by the author under the heading 'Puddled Steel: A Forgotten Chapter in the History of Steelmaking', J.I.S.I., vol.209 (1971), pp.785-789, pp.952-957.

2 British Patent No. 1420, 13th February 1784.

3 The most recent account is that of W. K. V. Gale, The Black Country Iron Industry (London, 1966), pp.125-132. Contemporary accounts are those of W. Truran, The Iron Manufacture of Great Britain (London, 1855), pp.130-146, B. Baylis, On Puddling - By a Practical Puddler (London, 1866) 56 pp., (published privately) and of the Welsh Trade Union leader William Lewis, under the name of Lewys Afan, The Tinman's Companion (Pontypridd, 1876), pp.121-154.

the main features of the furnaces at the Dowlais Works in South Wales in 1855.[1] This shows that the firegrate was separated from the working chamber by a bridge, so that the metal charged on the hearth, to the right of the bridge, was heated only by the flame and, provided an oxidising atmosphere, with sufficient excess air, was maintained, as was the normal case, the pick-up of sulphur from the fuel would be avoided. The hearth was lined with iron mixed with roasted puddling cinder from a previous operation; such a combination was obviously rich in iron oxide and relatively free from siliceous matter. Onto this hearth was charged some 300 to 500 lb. of pig iron, which was melted down under the action of heat from a coal fire on the adjoining firegrate. When molten, the metal was well 'rabbled'[2] to mix it with the fluid, highly oxidising, slag which formed. Under these conditions, much of the silicon, manganese and the phosphorus from the pig iron would be oxidised and held in the slag, but very little carbon would be removed at this stage. The metal still remained liquid and, on continued rabbling with the slag,

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1 This is redrawn from Truran, loc.cit., Plate 9.

2 A rabble was a long iron bar carrying at its end a stout rectangular piece of iron plate welded at right angles to the bar. By moving this to and fro through the metal and slag, the two could be brought into contact and stirred up together to promote their reaction; this process was 'rabbling'. The furnace tools were made from wrought iron, not simply because it was readily available but because it had the highest melting point of the relatively cheap metals.

eventually the carbon would begin to react. Bubbles of carbon monoxide would rise through the molten metal[1] and soon the reaction would gather momentum, the whole mass seething and slag running out of the furnace over the sill. Rabbling was continued and would become more difficult as the metal became less fluid, due to the removal of the carbon and the accompanying rise in melting point. At this stage, the level of the slag would subside, the bubbling would die down and the metal would exist as spongy clots within the liquid slag.[2] The metal could now be pulled together into 'balls', usually of about 60 to 80 lb. in weight, which were pulled out in turn and passed to the shingling hammer, where they were hammered or shingled into solid blooms, during which operation the bulk of the entrained slag would be forced out.[3] The bloom would then be reheated before rolling to give the required size of bar, whilst a further ball was being taken from the furnace for shingling. Obviously, this

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1 This was generally referred to as 'the boil' from its appearance in the furnace. The bubbles of carbon monoxide as they burst above the metal gave little blue flames, referred to as 'candles'.

2 This part of the process became known as 'coming to nature'.

3 The first few blows of the hammer on the more or less shapeless mass of metal granules and dripping slag were controlled in force; even so, the slag splashed out violently, necessitating the wearing of metal shin protectors by the hammermen. There is a patch of slag stuck to the wall at the back of the hammer, at Wortley Top Forge, some seventy years after work stopped there as a witness to the manner of its removal from the metal; this, incidentally, worked on reheated wrought iron blooms - the original shingling operation gave even more violent expulsion of slag.

was not only an arduous process but also one in which considerable skill and experience in regulating the temperature and the type of atmosphere in the furnace was essential, and the chimney damper was a very essential part of the equipment. Puddling furnaces could generally be recognised by their chimneys and Figure 30 shows a particular puddling plant which had some significance in the production of steel by the puddling process.[1]

Cort had originally expected that he would be able to produce steel by means of his furnace. It has to be remembered, however, that the distinction between iron and steel was only vaguely understood in his time. It slowly became clear, however, that by altering the conditions within the puddling furnace, particularly during the boil, it might well be possible to remove most of the impurities from cast iron and still retain sufficient carbon for the product to have some of the properties of steel, rather than those of wrought iron. It also became obvious that there were considerable niceties of judgement involved and the development of a suitable and reproducible technique for the production of steel, in this way, took many years and there were many valiant attempts which ended in failure. The technological background is a complicated one;[2] suffice it

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2 Some collected details can be found in Appendix TT.

to say here that the two main features of the successful process appear to have been the deliberate reduction of the oxidising power of the slag, by the replacement of a significant proportion of the iron oxide by manganese oxide[1] and by operating with a smoky, reducing atmosphere in the furnace, during the latter part of the process. In these ways the oxidation of the carbon was retarded.

It is clear that the process was of more importance on the Continent than in this country and much of the evidence is from European sources; the process was first developed in Germany and the last record of its use was in France. Eventually it was displaced by the large scale basic steelmaking processes; nevertheless, it obviously provided for the needs of industry for some time, in default of a better method, and it could produce a satisfactory steel from phosphoric pig iron, which is more than could be said for either Bessemer or Open Hearth

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1 This could be done, as was the case on the Continent, by operating on the high manganese pig irons (sometimes known as 'spiegeleisen'); it could also be achieved by additions of a mixture of manganese dioxide and common salt at intervals during the puddling operation. This addition was often referred to as 'Schafhautl's powder' since it was specified in a patent taken out by a gentleman of that name (British Patent No.6837, 13th May 1835). The mixture suggested by Low (British Patent No.10204, 25th May 1844) consisting of 42 lb. oxide of manganese, 8 lb. plumbago, 14 lb. of charcoal and 2 lb. of saltpetre (and which, as an addition to a closed crucible, we have already suggested might be somewhat exciting) was also recommended for addition to the puddling process in 2 to 3 lb. at a time, at intervals from fusion to 'coming to nature' to produce an iron which was stronger and more fibrous than normal - at least part way to puddled steel.

steel, up to 1880. It seems strange that it has been largely overlooked by almost all the writers of the histories of the iron and steel industry. It is intriguing, therefore, to endeavour to piece together the surviving evidence of a largely forgotten phase of steelmaking history.

The earliest reference to such an operation being practicable was a comment by the Director of the French Mint in 1823, to the effect that the greyest of the pig irons could be used to produce steel in a reverberatory furnace, by adding suitable oxides of iron to the molten metal.[1] Anton Schlegel, Works Director at Prevali in Carinthia, applied in November 1836 to the Austrian Government for a patent covering the production of steel from the puddling furnace.[2] A later critic implied that Schlegel showed a complete lack of knowledge of the puddling process.[3] This would appear to have had substance since the patent was not renewed. A year or two later, Franz Xavier Schmidt succeeded in producing steel at the iron puddling works at Weierhammer, in Bavaria. A description of this process survives[4] and has several points in common with later reports; it was said, however, to have given an

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1 M. Bréant, 'Une Espèce d'Acier Fondu', Bulletin de la Société d'Encouragement pour l'Industrie Nationale (1823), vol.xxii, p.226.

2 L. Beck, Die Geschichte des Eisens (Brunswick, 1889), vol.4, p.648.

3 H. Fehland, 'Geschichtliches uber die Puddelstahl Fabrikation', Stahl und Eisen (1886), p.225.

4 Fehland, loc.cit., p.226.

uncertain product, often containing soft streaks of iron. The same comments were applied to the product made in the Ruhr in 1839.[1] Morel, Petin and Gaudet carried out experiments in France in 1845,[2] as did Schneider at Le Creusot,[3] but all seem to have been, at best, only partially successful.

In 1849, however, Anton Lohage, a chemist in Unna, after two years of experimentation, joined forces with Gustav Bremme and Gustav Lehrkind and between them they established a reliable method. They were disappointed in their patent application in Prussia (due to prior leakage, probably by Lohage himself) but obtained rights in Austria, Belgium and other countries.[4] In the autumn of that year, Ewald Riepe, a London chemist, visited Lohage who allowed him to see the process in operation and then commissioned him to take out a patent on their behalf in London, which was duly arranged.[5] Thus, in this country, Riepe has erroneously been considered as the discoverer of the steel puddling process; Dr. Percy, indeed, refers to 'Riepe's Process'.[6] It should be noted that Riepe's patent makes a definite recommendation of

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1 Delvaux de Fenffe, 'De la Fabrication de l'Acier Puddlé en Allemagne', Revue Universelle (1857), vol.1, p.60.

2 C. Lan, 'Études sur les Reactions de l'Affinage des Fontes pour Acier et pour Fer', Annales des Mines (1859), vol.xv, p.104.

3 Beck, loc.cit., p.649.

4 O. Johannsen, Geschichte des Eisens (Dusseldorf, 1953), p.373.

5 British Patent No.12950, 29th January 1850.

6 Percy, loc.cit., p.793.

> 'not raising the heat above cherry redness or the welding heat of shear steel'.

This was certainly in keeping with the earlier ideas of Bremme but he had been revising his opinion and, by the time the British patent was issued, had decided the process worked better at a higher temperature. This discrepancy was to lead to a rather curious situation a few years later, as will be indicated. Riepe's patent was taken up by the Low Moor Company and Lohage, Bremme and Company sent Herr Fehland, an expert in the process, to instruct them. A translation of his report reads as follows :[1]

> 'The steel working at Low Moor began on 13th October 1851. The puddling furnaces had preheating hearths which were very small and terrifically hot, so I did not find it necessary to alter anything, in contrast to what had to be done by me at all the works I visited earlier or later. As in iron puddling at that time here, 300 lb. of pig iron were put in and on 16th October, from 6.20 a.m. to 5.30 p.m., ten heats were made and a total of 2796 lb. of steel balls were taken out, which corresponds to a waste of about 6¾%. The raw iron was charged into the preheater as soon as the metal in the furnace had balled up and shown grain. The steel was pressed together like butter and welded extremely well'.

What Low Moor did with their puddled steel, how long they went on producing it and how much they made are all unknown. The only relevant comment seems to

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1 Fehland, loc.cit., p.228.

have been made by a Mr. Vickers, of Naylor, Vickers and Company, in the discussion of a paper presented in 1858[1] in which he stated that

> '.... the puddled steel manufactured by the Low Moor Company has not come into much use, owing to the high price they had put on it'.

He went on to say, however,

> 'Cast steel made from puddled steel is more malleable than the generality of English iron converted into steel and is well adapted for shafts, spindles and other portions of machinery. I have also used it extensively for cast steel bells'.

We do know, however, that the Mersey Iron and Steel Company also took up the patent, since the paper just mentioned was on puddled steel and was given by William Clay, the energetic and forthright owner of those works. Clay, having quoted the Riepe specification verbatim, went on to say :

> 'From the first commencement there has been found no difficulty in heating, forging or rolling this steel into any form or shape, as it has been made into steel plates, bars, angles, rivets, rails, railway points and forgings of all kinds with perfect ease and with success and, ever since the manufacture

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1 W. Clay, 'On the Manufacture of Puddled or Wrought Steel, with an Account of Some of the Uses to which it has been Applied', Journal Society of Arts (1857-58), vol.VI, pp.140-148. It is interesting to note that this appeared in translation into French as 'De La Fabrication et de l'Emploi de l'Acier Puddlé' in Revue Universelle des Mines (1858), pp.301-314.

> was commenced at the Mersey Steel and Iron Works, this steel has been used for almost anything that was required to be of a strong and durable nature or to repair any of those breakages which are of such constant occurrence in every iron work. It is somewhat worthy of remark that, although this process is so novel and, apparently, of so delicate a nature, yet, with the specifications as my only guide, having never before heard of or seen the operation, it succeeded perfectly in the first trial which was made, and produced so excellent a steel that, after working about 100 tons, it has hardly been surpassed. I have used pig iron of all descriptions, North Welsh, South Welsh, Staffordshire and Scotch, with the same result, viz. the production of excellent steel: but I have not found, so far, anything like the difference that I expected between hot and cold blast iron. Most excellent results have been obtained from both; this is more particularly important as it shows that the extent to which this manufacture may be carried need not be circumscribed by the very limited supply of cold blast iron'.

He then went on to discuss its various uses: ordnance, naval chains, boiler plates, girders, bridges - all made satisfactorily of puddled steel. There are no indications of production levels, other than the original reference to 100 tons, but this clearly is no small scale operation. Clay concludes his paper as follows :

> 'I do not for a moment anticipate that the steel manufactured by this process will supplant the best description of steel, but I feel confident that it must come largely into use for the most ordinary purposes, where cast steel, from its great cost, cannot be used. Indeed, if I might indulge somewhat in prophecy, I would express the belief that, in a few years, the manufacture of this wrought steel will have become as important a branch of our national industry as that of iron now is'.

This seems to put the material into context in the engineering field: a superior type of wrought iron with higher strength, and thus having important weight-saving characteristics, but no replacement for crucible steel for specialised applications. His prophecy was, in part at any rate, correct; the material which displaced wrought iron, however, was not puddled steel but 'mild steel' produced by the Bessemer or Siemens Open Hearth processes. That, however, was some years ahead when Clay wrote, and puddled steel had, in the interim, its part to play.

Meanwhile, further work had been carried out on the process for steel puddling. In 1852 a patent was filed in the name of Collins[1] on the basis of information communicated to him by a foreigner, said elsewhere to be Bremme. This referred to the exposure of the material in the puddling furnace

> '.... to a very high degree of heat by which the impurities less the carbon are burned ....'.

This appears to have been the method now favoured by Bremme, who is said to have quarrelled with Riepe. Riepe, on the other hand, now seems to have been a sick man and not able to prosecute the active promotion of the patent, according to Clay. Within

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1 British Patent No.14033, 22nd September 1852.

just over a year Bremme used Brooman as his agent to obtain a further patent.[1] This specification opens as follows :

> 'Steel manufactured in reverberatory furnaces has been found not to answer all the purposes to which it might be applied; for steel so manufactured is neither sufficiently pure nor strong for universal uses and is in some cases useless. These defects arise from the steel being manufactured at a cherry red heat at which the silex does not sufficiently separate from the metal. To effect this separation, a certain fluidity or softness is required which is only attainable at a much higher heat. Moreover the scoria which is mixed with the steel in the reverberatory furnace does not possess the fluidity necessary for its separation under hammers or rolls. Now the present invention is intended to remedy these defects and consists in manufacturing steel in reverberatory furnaces by the following process. Puddling is commenced at the highest attainable heat; the temperature should be raised to a white heat, or as near to that as possible, and cannot be too high towards the end of the operation. It is not, however, always possible for the workman to obtain a white heat on account of the atmosphere or of defects in the furnace. Yellow heat would yield a satisfactory result and must be considered as forming part of the process in contradistinction to those processes above alluded to where a cherry red heat is adopted'.

It is alleged that Riepe took legal action against Brooman, claiming that the two patents were identical; his lawyer claimed that what looked like a cherry red temperature in bright sunlight would appear as a yellow, or even white, heat in a darkened shop! Unfortunately, the outcome of

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1 British Patent No.243, 31st January 1854.

this wrangle is not known; whatever it may have been, it seems clear that the higher temperature was the correct one, all later records confirming this.

The process was, by this time, gaining momentum on the Continent. A paper appeared in France in 1857 summarising the work done on puddled steel to date in Germany.[1] This reported that in 1854, the province of Westphalia, which at that time was responsible for over 90% of Prussian steel output, produced 5957 tons of 'natural steel', 3878 tons of puddled steel and 2610 tons of cast steel, the puddled steel representing an increase of 1263 tons over that in the previous year. It is also reported elsewhere[2] that in France the puddled steel production exceeded the total made by all other methods. This is confirmed by the official statistics;[3] these cover the steel production in France, district by district, for the years 1853 to 1859, dividing the production into 'acier forgé', 'acier cementé' and 'acier fondu'. The figures in metric quintals[4] for the

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1 De Fenffe, loc.cit., p.59.

2 D. S. Landes, The Unbound Prometheus (Cambridge, 1969), p.254. The same reference implies that the 'scissor year' came at least as early in Germany.

3 Ministere de l'Agriculture, du Commerce et des Travaux Publiques, Statistique de l'Industrie Minerale: Resumé des Travaux Statistique de l'Administration des Mines en 1853, 1854, 1855, 1856, 1857, 1858 et 1859 (Paris, 1861), pp.484-499.

4 The quoted figures divided by 10.15 would give English tons.

Loire district are as follows :

	1853	1854	1855	1856	1857	1858	1859
Acier forgé	Nil	Nil	13000	21136	65595	74741	72160
Acier cementé	80430	86300	74331	37698	42480	32468	30260
Acier fondu	58545	63545	48609	37252	43091	39267	26290

It is logical to assume that the old practice, in the Loire, was much the same as in Sheffield and that the cast steel would be produced by the remelting of blister steel at this date; any excess of 'acier cementé' over 'acier fondu', therefore, could be assumed to have been used after forging or rolling to supplement the product of the 'acier fondu'. Thus in 1853-4 about 73% of the production was in cast steel. 1855 saw the introduction of puddled steel[1] and by 1856 the excess of blister steel over cast steel had been almost wiped out, indicating that puddled steel had taken over the more routine applications and was, by then, responsible for some 36% of the total production. In the next two years there was an excess of cast steel over blister steel, the inference being that instead of blister steel, some puddled steel was being remelted in crucibles, and in 1859 some 70% of the total steel was puddled.

The figures for the total French production cannot be as safely assessed since the term 'acier forgé' also includes any production by the old established 'natural steel' methods. The figures for 1853-4, however, are around the 40,000 metric

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1 Beck, loc.cit., p.897, indicates that the Germans introduced steel puddling into the Loire works between 1854 and 1855.

quintal level and from 1855 there is a steep rise. This, on the other hand, is little more than the effect of the rise in puddled steel in the Loire district. The total effect on the French steel industry seems to be a halving in the product of the cementation furnace output, a reduction of almost 40% in the output from the crucible furnaces and a build up of puddled steel production both to fill these gaps and provide an overall increase in production of some 10-20%. Such was the impact of the introduction of puddled steel in France over a five year period. It is also interesting to note that the cost of puddled steel from the Loire district was estimated to be only about 80% of that of the natural steel from the Isère - 340 francs per 1000 kg as against 430 francs. At the same time, the natural steel from Styria and Carinthia was even more expensive at 450-500 francs per 1000 kg.[1]

The earliest corroborative evidence for the French involvement in the steel puddling process comes from the patent taken out by Tessié de Motay and Jean Fontaine within a year of the introduction of the Loire activities.[2] The specification seems to be a combination of the Riepe

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1 L. E. Gruner and C. Lan, <u>L'État Present de la Métallurgie du Fer en Angleterre</u> (Paris, 1862), p.743.

2 British Patent No.535, 1st March 1856.

and Brooman details with the use of Schafhautl's salt and other nostrums, including alkali carbonates. There were, however, three important papers published in France in 1859. One, by Lan,[1] covered the reactions during refining; a second, by Janoyer,[2] covered the technological aspects and the third, by Gruner,[3] dealt with general aspects of production and the role of steel puddling in its overall context. Then in 1861 came a French treatise of a practical nature dealing with the puddling process and its application to both iron and steel.[4]

In this country it is also clear that the use of the process increased over the same period, since Percy,[5]

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1 Lan, loc.cit., pp.85-146.

2 M. Janoyer, 'Mémoire sur la Fabrication du Fer a Grains et de l'Acier Naturel aux Fours a Puddler', Annales des Mines (1859), vol.xv, pp.147-167. He comments in his introduction that puddling for steel is, without fear of contradiction, one of the most important recent conquests in the iron and steel industry.

3 L. E. Gruner, Notes Diverses concernant l'Acier Puddlé et l'Acier de Forge', Annales des Mines (1859), vol.xv, pp.291-336.

4 L. Ansiaux et L. Masion, Traité Pratique de la Fabrication du Fer et de l'Acier Puddlé (Liège, 1861). The process for the puddling for steel is covered by pp.64-76 and the author's translation of the relevant passages will be found in Appendix UU.

5 Percy, loc.cit., p.791.

writing in 1864, gave his considered opinion that

> 'puddled steel is now an article of great commercial importance'.

Some fifteen years later, however, it was stated that[1]

> 'the production of steel by the process of puddling has almost entirely been superseded by the more simple, reliable and economical processes of the pneumatic converter and the open hearth; but the puddling process has, nevertheless, continued to be one of the practical aspects of steel manufacture and one that may fairly claim a high degree of consideration'.

The author of this last quotation gives some most intriguing information: in discussing the use of steel for ship plate, he gives details of vessels constructed over the past twenty years with steel, at least in part, in their make-up. Of the first twenty vessels listed, no less than fourteen contained puddled steel.[2] He also lists the steel suppliers: in addition to the Mersey Steel and Iron Company, production of puddled steel was carried on by the Weardale Iron Company, as well as by the two Sheffield steelmakers, Thomas Firth and Sons, who supplied angles and plates in 1861, and John Brown and Company, who supplied plates from 1859 to 1861 as well as 'Atlas toughened steel' from 1864 to 1866. From other evidence, it is known that John Brown

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1 Jeans, loc.cit., pp.518-522.

2 The 'Atlas toughened steel' supplied by John Brown and Company was also probably puddled steel.

installed puddling furnaces in 1858[1] and that further additions of such furnaces were made in the next three years, eventually making a total of 72.[2] At the same period, his neighbour, Charles Cammell, also installed puddling furnaces and the tradition is that these were both designed for the provision of wrought iron for armour plates; Cyclops works eventually had 60 puddling furnaces. John Brown, however, always 'had an eye for the main chance' and it is now quite evident that he produced steel as well as wrought iron from his puddling furnaces. He was supplying steel melting base to some of the smaller Sheffield crucible steel melters in the 1860s and it is a reasonable assumption that this was also puddled steel.[3] Thomas Firth and Sons were not armour plate manufacturers - they made projectiles to penetrate the armour supplied by their neighbours! Nevertheless, they set up a works with 18 puddling furnaces in 1856 at Whittington, near Chesterfield.[4]

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1 J. Hunter (ed. A. Gatty), The History and Topography of the Parish of Sheffield (Sheffield, 1869), pp.214-215.

2 S. Griffiths (ed. W. K. V. Gale), Guide to the Iron Trade of Great Britain, 1873 (Newton Abbot, 1967), p.279.

3 This is listed on a number of the price lists issued by Doncaster's in the 1860s and also appears in the Brittain Accounts (Sheffield City Libraries, SD 266).

4 A. C. Marshall and H. Newbould, The History of Firth's, (Sheffield, 1924), p.22. The works is illustrated in Figure 30.

> 'At these works, the manufacture of Firth's famous puddled steel was carried out .... (it) had the reputation of being the finest made in the country and they supplied Wentworth's, Vavasseur's and Armstrong's, besides the Government works at Woolwich'.

The Whittington Works, incidentally, were closed in 1887.

Operations in the Sheffield area receive mention in two French reviews. In the survey of 1862[1] there occurs a passage which may be translated as follows :

> 'From the time of the introduction of puddled steel in Sheffield may be dated the production of rails, tyres and large plates in steel, not before produced in this area. Also, following the introduction of this process, cast irons flow into Sheffield from all parts of the globe: charcoal irons from Sweden, Canada and India, alongside coke irons, cold blast or hot blast, from Wales or Staffordshire'.

The same report also assesses the costs of production of puddled steel in Sheffield as follows :[2]

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1 Gruner and Lan, loc.cit., p.769.

2 Gruner and Lan, loc.cit., p.796. The figure for profit has been assessed in accordance with the selling price quoted on p.805 of the report. Prices are quoted for other pig irons. Charcoal smelted irons from Russia, £9.8s; from India, £6.18s; from Canada, £9.15s; home produced from Argyll or Lancashire, £8-£9. Coke smelted iron from Blaenavon, Lancashire or Cumberland is quoted at £4-£6 per ton. All prices are for material delivered to Sheffield.

1.20 tons cast iron from Sweden @ £7.8.0. per ton	£8.17. 7.
1.60 tons coal @ 9s. per ton	14. 5.
Labour	17. 0.
Maintenance of furnace and tools	7. 7.
Various general costs	8. 0.
Interest on capital	8. 0.
	£11.12. 7.
Deduct return from bar ends, cinder, etc. say	8. 0.
	£11. 4. 7.
Profit say	1. 5. 5.
	£12.10. 0.

For John Brown to sell such puddled steel as melting base at £13 to £14 per ton would, therefore, be quite reasonable. The other report[1] states that John Brown and Company made fine iron, for armour plates, and puddled steel for springs and tyres.

Puddled steel was quite possibly made by R. F. Mushet at his 'secret' steelworks in the Forest of Dean; it was definitely made at Ebbw Vale by George Parry. He made the very valid point that the puddling process was quite capable of removing phosphorus from the pig iron, which Bessemer's process most definitely was not. In his paper of 1863[2] he gave the analysis of a sample of puddled steel together with that of the pig iron from which it was produced :

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1 S. Jordan, Revue de l'Industrie du Fer en 1867 (Paris, 1871), vol.4, p.329.

2 G. Parry, 'On Puddled Steel', Proc. South Wales Inst.Eng. (1862), vol.iii, pp.74-81.

	Pig Iron	Puddled Steel
Carbon	2.68%	0.50%
Silicon	2.21%	0.11%
Manganese	1.23%	0.14%
Sulphur	0.125%	0.002%
Phosphorus	0.426%	0.096%

The material was intended for use as railway springs and must have been quite suitable for this application, when correctly heat treated. Parry made another valid suggestion to the effect that, if further phosphorus removal was desired, this end could be achieved by remelting wrought iron scrap in a cupola with coke, so as to recarburise it, casting into slabs and re-puddling it.[1]

Very little is known of the later history of the process in this country. It appears, however, that in 1868 John Gjers at Middlesbrough was puddling steel from Linthorpe No.3 iron and that James Kitson was making puddled steel at Monkbridge in 1876.[2] In addition, it is significant that most of the patents taken out relating to improvements in wrought iron production in the twenty years up to 1878 - many of them dealing with

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1 British Patent No.2900, 18th November 1861.

2 Both these items of information come from private communications received by Dr. Percy, when he was collecting together information for his projected revision of his treatise on iron and steel. The full collection of papers is held by The Metals Society in London; I was allowed to study these by courtesy of Maurice Pearl, Esq.

attempts to mechanise the process - indicate quite clearly that they are equally applicable to the manufacture of steel as well as iron. One of the latest of these came from William Clay and could indicate that his control of the straightforward process was not as close as he would desire; at the same time it shows clearly the interest in the process as late as 1877.[1] He couples with the puddling process the old mid-European practice of feeding, into the already decarburised iron,[2] a measured quantity of pig iron, which may be premelted or in granular form, and working it into the iron to recarburise it to the desired level prior to balling and shingling. There is also a record of the reminiscences of a Staffordshire man, recalling the production of puddled steel for springs for railway and road carriages.[3] The date and the site of such operations are not indicated. Reference is made, however, to the use of Cumberland or Hodbarrow ore, for fettling, and pig from Barrow, Forest of Dean, Tredegar and Blaenavon - all low phosphorus materials. The only physic used was agricultural salt at the rate of 2¼ lb. per 4¼ cwt. heat of

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1 British Patent No.1742, 4th May 1877.

2 He implies that the charge should be brought to nature in the ordinary manner, which is taken to indicate that he would proceed as though he were producing wrought iron prior to working in further cast iron if steel was required. This, of course, is a simpler matter and a more reproducible one than trying to control the degree of decarburisation.

3 M. Millard, 'Old Methods of Ironmaking', Journal Staffs. Iron and Steel Inst., (1911-12), vol.xxvii, pp.188-191.

pig iron. The process described follows normal practice, with particular reference to working with a furnace full of a dark dense flame and the removal of the balls as quickly as possible, once they were ready. The bars after shingling were tested by placing on a block of iron and striking with a good sized hammer; if the bar broke readily into two or three pieces, with fine, clear crystals, it was considered good; if it did not break, the puddler's attention would be called to it.[1]

Information on German production of puddled steel is to be found in a description of the Krupp Works at Essen in 1866 :[2]

> 'The ore employed is obtained partly from Krupp's own mines at Nassau and near Coblenz and is partly bought. The former is spathic, furnishing the well known Spiegeleisen; the latter is red oxide. The iron is converted into steel by puddling; a small quantity of cemented steel is also occasionally used. A little malleable iron is made by a modification of Bessemer's process, but no steel. Mr. Bessemer offered his patent to Mr. Krupp, as I understand, but it was then in its infancy and was not considered so promising as to divert the latter from his own speciality, the puddling process. He

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1 If it were too ductile to break easily, this would clearly indicate that the decarburisation had been carried too far and the product was iron rather than steel. If, on the other hand, the material had been insufficiently decarburised, it is doubtful whether the high carbon material would forge under the shingling hammer and there are indications, elsewhere, that such material would be returned to the furnace and retreated along with further pig iron.

2 C.B.B., Letter to The Times, Thursday, 8th September 1866.

has not, therefore, carried it to such a forward condition as has been attained by some of our iron-masters at home.

Though the Spiegeleisen contains such a large proportion of manganese, a mere trace is left after puddling as shown by Mr. Abel's analysis given below :*

Carbon (combined)	1.18%
Silicon	0.33%
Sulphur	None
Phosphorus	0.02%
Manganese	Trace
Cobalt and Nickel	0.12%
Copper	0.30%
Iron (by difference)	98.05%

The puddling I did not see, but was assured that there is no material difference from the process well known in Sheffield, though some of the details vary somewhat. The metal which is worked into guns and other products required to stand sudden shocks must, of course, be softer than for such as have only to resist steady rubbing work and this softness is attained by mixing a certain proportion of wrought iron with the steel to be melted for casting'.

Much more detail on the operations at these works and, incidentally, clear proof that the process persisted in Germany to the end of the century at least, can be found in a later publication.[1] This also quotes the dictum of Alfred Krupp :

'In my factory second rate material will not be used and shall not be made'.

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* There is a footnote to the article to the effect that Herr Piesser, manager of the Krupp's works, informed the writer that analysis made at Essen gave copper trace to 0.15%. Mr. Abel, incidentally, was chemist at the Woolwich Arsenal.

1 F. G. Muller, Krupp's Steel Works (London, 1898), pp. 33-35. This volume is stated to be an "authorised translation from the German". The paragraphs describing the puddling process for steel production are reproduced as Appendix FFF.

Further information concerning the production of puddled steel in France is also available. In 1877 there were 51 puddling furnaces for steel (as against 995 for iron) and six open fire refineries for the production of natural steel, the combined output of puddled and charcoal refined steel being some 20,373 tons in the year. Ten years later, however, there were only 35 steel puddling furnaces and five refineries, with a joint production of 12,532 tons. The manufacture of puddled steel at the later date was mainly in the Loire district, the firms involved being J. Holtzer at Unieux, Firminy at St. Chamond, the Chatillon Commentry works at Montlucon and the Dieulouard works of Gouvy and Company. There is a comment in this report that the annual output of puddled steel was now very small compared with formerly and that the process was gradually disappearing.[1] In 1900, however, [2] puddled steel was still being produced at Assailly, Unieux and Montlucon and an impressive exhibit of agricultural items, including forks, shovels, plough fittings, cart tyres and so on, all in puddled steel, was put on by Gouvy and Company of Dieulouard. It was a descendent of these proprietors who reported on puddled steel as late as 1955. Styling himself as 'Maitre de Forges de la Maison Gouvy', and pointing out that his firm

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1 S. Jordan, 'The Iron and Steel Manufacture in France in 1887', J.I.S.I. (1889, Part 2), pp.20-22.

2 H. Bauermann, 'Iron and Steel at the Universal Exhibition, Paris 1900', J.I.S.I., vol. LVII (1900), pp.160-168.

had been a producer of good steel since 1751, Monsieur F. Gouvy presented a paper whose sub-title could be translated as 'The Evolution of Steelmaking Methods'; an extract from the comments of one with first hand knowledge of the process is a fitting conclusion to the historical survey :[1]

> 'Among the first to do so on the Continent, around 1840 the House of Gouvy applied to steelmaking the process of puddling as used in England for making iron, varying the quality according to the method of forging and suiting the product to the various uses for which the steel was destined. This process was still functioning at our works at Dieulouard in 1914, with five puddling furnaces, despite the competition of the Thomas and the Martin steel. The process was as follows. Charges of 250 kg made up of cast irons carefully chosen according to the quality of steel required having been charged to the furnace hearth at the same time as the necessary slag, the action of gas from a coal fired producer decarburised the mass. The campaign continued with four charges in twelve hours and with two teams of three men comprising a master puddler, a shingler and a helper. The master puddler had command of the furnace, the firegrate, the gas producer and the laboratory and, above all, rabbled the bath to bring together the loupe* of steel resulting from the operation; this he cut into four parts. These went to 1500 kg hammers fed with steam from boilers placed on the furnaces. The blooms so shingled were classified into various types of steel and passed forward to be reheated and made into bars, under the control of the master puddler. These bars, made into faggots of 75 kg, were forge welded under a

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1 F. Gouvy, 'La Maison Gouvy depuis sa Fondation jusqu'à Nos Jours: Évolution des Methodes de Fabrication des Aciers', Le Fer a Travers les Ages (Nancy, 1956), pp. 351-352.

* The French term 'loupe' came into use as an alternative for what would be called the 'ball' in this country. It has its origins, however, in the much older natural steel finery practice in Central Europe.

> 5000 kg hammer into a single block destined for the rolling mill.
>
> The number of these forging operations so carefully controlled gave a material of irreproachable quality but its somewhat high cost little by little brought about the disappearance of this process in face of the improvement of quality and the efficiency of the Thomas and Martin steelmaking processes. We had, ourselves, constructed Martin furnaces from 1899 but, nevertheless, our customers preferred puddled steel right up to the 1914-1918 War.
>
> The craftsmanship and knowledge of the secrets of the process were an adequate substitute for the measuring instruments so much in use today, without any prejudice to the quality of the product, which was probably higher than that of the modern processes. It was easier to guarantee the tools made with such steels'.

The manufacture of puddled steel was, quite clearly, an important contribution to the engineering industry between 1855, when it came into prominence in Europe, and 1880, when it was pushed into a minor role by the introduction of the basic bulk steelmaking processes. It had possessed an advantage over the original Bessemer and Open Hearth processes, with their 'acid' linings, in that it could produce relatively low phosphorus steel from phosphoric pig iron and, provided the application was one not involving critical stress patterns - in general, where wrought iron could be used if in sufficient mass- it could be used with advantage over wrought iron on account of its enhanced strength, making thinner and less weighty constructions possible. In addition, it was perfectly suitable for applications such as agricultural tools, vehicle springs, railway locomotive and carriage tyres and axles, marine shafts, lock and harbour installations and even boilers. Thus, up to 1880, puddled steel could, in a sense, be considered as being complementary to Bessemer steel, the one for dealing with phosphoric irons and the other with haematite irons. This, in turn, explains why the puddled steel process assumed more importance on the Continent since low phosphorus ores were relatively scarce in both France and Germany. Thus, although the making of steel in this way has now been almost forgotten, its value at the time should not be underestimated; it most certainly contributed to the division of the steel industry, in the second half of the nineteenth century, into the bulk steel and the special steel sectors.

IV Methods Involving the Melting Together of Cast Iron and Wrought Iron

A method of this type has already been described as a development of the original Huntsman crucible process and various modifications to this concept were proposed over the years.

The real step forward, however, as regards bulk steel-making, came with the introduction of the 'Open Hearth' furnace. Provided with regenerative chambers, whereby producer gas could be burned within the furnace and the hot spent gases used to heat up the regenerators at one end, the reversal of the gas and air flows after, say, twenty minutes, would allow the gas and the air each to be pre-heated separately before mixing in the furnace, thus giving a hotter flame as well as fuel economy.

The earliest use of such a furnace, other than as a replacement for the conventional coke fired crucible melting furnace, for the melting of steel seems to have been by Charles Attwood at Tow Law in 1862.[1] Here, in a furnace built by Siemens, cast iron and malleable iron[2] in appropriate proportions were melted together on the open hearth to give the required carbon content in the bath, making a particular point of preferring

> 'that variety of bright and white cast iron of a crystalline and highly lamellar structure and almost silvery whiteness which is called in England 'specular iron' or by its equivalent German name 'spiegeleisen', as that iron is remarkably uniform as respects the proportion of carbon it contains and is generally of highly superior quality, containing a less proportion than most other sorts of the matters or ingredients which are injurious to the quality of steel'.

In this connection, it is worth noting that Attwood was

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1 The details quoted here are given in British Patent No. 1473, 15th May 1862. It should be noted, however, that the patent covered melting such mixtures in conventional crucibles, to be taken from the hearth as well as melting in larger vessels which 'might be tapped at their bottoms without being removed from the furnace' in addition to the embryo open hearth process itself.

2 'Malleable iron' was another term for wrought iron; it should be distinguished from 'malleablised iron castings'. Both, however, tended to be referred to as 'malleable iron'.

operating on the Weardale brown ores in his blast furnaces; such ores were rich in manganese and low in phosphorus. His alternative was to take grey cast irons, preferably charcoal smelted, and to put these through a 'finery' to give 'refined metal' which, by partial oxidation, would remove most of the silicon. As regards the proportions of cast iron to malleable iron, these could vary from 6 to 10% cast iron for the softest steels to 30 to 40% for hard steels. Attwood also added a certain amount of 'cullet'[1] with his charge, so that when molten it would be protected by a layer of more or less inert slag. A special point was also made of the possibility of incorporating steel scrap of suitable quality with the charge. When fully molten, the metal was run out through a tap hole leading from the lowest point of the hearth into a ladle, from which it was poured into ingot moulds, or even into sand moulds to produce castings.

This early trial was soon followed by a more elaborate process, worked out at Seraing in France by the two brothers, Pierre and Emile Martin, in a furnace again built for them by Siemens. Originally they melted cast iron on the open hearth and then melted in scrap iron or steel or turnings, but with a preference for puddled balls, charged cold or sometimes preheated. They then ran off half the metal and cast it, and then

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1 'Cullet' is broken glass.

fed in more cast iron and more scrap or puddled balls. An important part of the process was the use of a fluid protective cover made from blast furnace slag, with additional lime or alumina as necessary. In such a manner, the furnace could be kept running continuously for a week or more.[1]

After a while, however, the continuous process was abandoned in favour of a batch process[2] which they described as follows :

> 'In a reverberatory furnace .... heated by gas according to Siemens' method, and raised .... to a continuous white heat, I place about 700 lb. of cast iron in pieces, each piece weighing about 4 lb., and a bath of liquid cast iron at a high temperature is obtained; into this bath I introduce, by degrees, pieces of puddled steel in blocks of 2 to 4 lb. until about 200 lb. has been added. Fifteen to twenty minutes suffice for the fusion of these 200 lb; .... I then add a second charge of puddled steel heated to white heat and always by degrees; after a third charge of steel has become fused in, I take off the black oxidizing scum on the bath and replace it by a clear vitreous scum, such as that from a wood heated blast furnace, and add an equal weight of siliceous sand. The scum preserves the bath from oxidation while the sand prevents the metal becoming short or brittle. I continue to add to the bath the doses of 200 lb. of blocks of puddled steel as before stated as fast as their fusion will admit, for instance 3400 lb. arising from 700 lb. of cast iron, 2300 lb. of puddled steel and 400 lb. of debris or pieces of

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1 These details come from a patent taken out in this country on behalf of Pierre and Emile Martin by R. A. Brooman (British Patent No.2031, 15th August 1864).

2 British Patent No.2137, 18th August 1865, was also taken out by Brooman on their behalf.

> steel from previous fusions. At this stage the whole is stirred, the metal tested by portions drawn from the bath and, according to its quality, I add from 40 to 100 lb. of similar cast iron, previously heated to white heat, which fixes the exact grain of the cast steel. To raise the temperature of and purify the bath at the end of the operation if necessary, I introduce a flux of manganese and sea salt and fluorspar melted together, in the proportion of two parts by weight of sea salt to one part of fluorspar. The metal, stirred and brought to the right degree of quality, is run into moulds or ingots ....'.

There follows a description of the casting operations, with moulds on a roundabout so that they may be filled in succession from the furnace spout. The commentary then continues :

> 'For a .... furnace of about 4000 lb. capacity the duration of the operation is from five to six hours, which allows two successive fusions in twelve hours and therefore twenty four fusions per week; it is necessary, however, to have two furnaces since each requires repair after ten to twelve fusions. The waste is about ten to twelve per cent, according to the nature of the materials employed. The consumption of coal is about thirty three bushels in twelve hours, but anthracite, lignite, peat or similar materials may be substituted. It is also necessary to add about thirty three bushels in twelve hours for the furnace for reheating the pieces of cast iron or puddled steel before introducing them into the bath .... The proportions of cast iron and puddled steel may be varied according to the nature of the cast steel to be obtained; all pure steely cast irons, that is to say, those which give puddled steel of good quality, will produce, by this process, good qualities of cast steel. Likewise good steel is produced from natural irons and steels refined by wood'.

The patent clearly indicates that the example quoted above will produce a 'semi hard' steel; by using puddled iron rather than puddled steel in the fusion, a soft steel was obtained which it is stated 'would not temper'.

This, then, was the Siemens-Martin process, also known as the Pig and Scrap process. It will be clear that the method draws on the steel puddling procedures as well as on the experience of melting in crucibles. It should be quite clearly noted that the addition of iron ore to the slag (other than a passing suggestion that a small addition could assist in dealing with any pieces of cast iron which tended to float in the scum) was not a feature of the process, which was purely a melting operation, just as the admixture of cast iron and bar iron in a crucible charge was a melting operation, without any effort being made to change the composition of the charged materials. In this way, the Siemens-Martin process differed significantly from the Siemens Open Hearth process which superseded it. There is no doubt, however, that the Martin Brothers made a most valuable contribution to the development of steelmaking history.

V Methods Involving the Decarburisation of Cast Iron to produce Liquid Steel

This category covers the two major successes in the search for bulk steelmaking and those which gave the foundation of the modern steelmaking industry, eclipsing all but the crucible process by 1880, namely, the 'pneumatic process' due to Bessemer and the 'open hearth process' of Siemens.

It is not the purpose of this discussion to enlarge on these processes, which are more than adequately described in any text book on steel, but it is useful to look at their technological basis and their early history, so as to place them in context of the changing nature of the industry.

In both the processes liquid blast furnace metal was oxidised so as to remove the carbon; incidental to this was the removal of both silicon and manganese. In the Bessemer process the oxidising agent was, ostensibly, a blast of air; the oxygen in the air gave rise to a rapid burning out of the carbon and the other elements. At the same time, this combustion gave rise to sufficient evolution of heat to raise the temperature sufficiently so that the metal remained fluid, despite the rise in melting point which accompanied the removal of the impurities. In actual fact, however, the first stage of the burning out process was the oxidation of some of the iron present; the iron oxide so formed then reacted with the carbon by the reaction which should now be familiar,[1] producing carbon monoxide gas which then burned at the mouth of the converter.

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1 The reactions may be expressed as follows :

$$2Fe + O_2 = 2FeO$$
$$FeO + C = Fe + CO \text{ (gas)}$$

At the same time the manganese and silicon are oxidised :

$$Si + 2FeO = SiO_2 + 2Fe$$
$$Mn + FeO = MnO + Fe$$

From this silica so produced, plus further silica dissolved from the furnace lining, a liquid slag would also be formed, consisting of a mixture of silicates, which in their simplest form may be represented as follows :

$$2MnO + SiO_2 = Mn_2SiO_4$$
$$2FeO + SiO_2 = Fe_2SiO_4$$

Meanwhile, the carbon dioxide brought into contact with air burns with a blue flame :

$$2CO + O_2 = 2CO_2$$

In the Siemens process the reactions are essentially the same, except that the source of the iron oxide is the added iron ore rather than the oxidation of some iron by the oxygen of the air in the Bessemer process. In the Bessemer process the process is a cyclical one: iron is oxidised, the iron oxide reacts with carbon, etc., producing the oxide of the other elements and releasing the iron again as metal, the nett effect being the reaction of the oxygen from the air with the carbon, silicon or manganese. There is, however, always some loss of iron to the slag. In the Siemens process, however, the iron oxide is added as such and there is, therefore, additional metallic iron produced as the other elements are removed.

In the Siemens process, the cast iron was melted in a similar manner to that described in the Siemens-Martin process and this produced a similar type of slag (or 'scum' as previously described). The difference, however, between the two processes lay in the subsequent addition of iron ore to the slag. This increased the iron oxide content of the slag and eventually this would start to react with the carbon present in the liquid metal below the slag, the reaction taking place at the slag-metal interface. The carbon monoxide, however, in this case had to escape to the surface through the slag and, as the bubbles burst there, they caught fire. The resulting commotion gave the impression that the contents of the furnace were actually boiling and this stage of the process was, therefore, known as the 'boil'.

One major difference between the two processes lay in the time taken. The Bessemer 'blow' was over in twenty minutes or so, whilst the Siemens 'heat' took anything from four to twelve hours, depending on the type of charge, the desired carbon content in the steel and the size of the furnace. Control of analysis could thus be expected to be much easier in the Siemens process. Control of the Bessemer steel analysis was mainly arrived at by burning out all the carbon and then adding sufficient spiegeleisen or other suitable addition to provide the required carbon and to deoxidise the metal.

The Siemens process was much more flexible. The slag composition could be controlled with regard to its oxidising capability. To make it more oxidising, more iron ore was added; when it was required to slow down the reaction small additions of limestone could be made, instead, and it was also useful to have a high manganese oxide content to slow down the oxidation.[1] When the boil had slackened, an addition of spiegeleisen could be made to stop the boil entirely.[2] The carbon content could then be adjusted, either by melting in the necessary pig iron or even by adding crushed anthracite or some such carbonaceous matter to the steel stream, on tapping the metal from the furnace.

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1 The effect of manganese has been discussed earlier; here, the manganese oxide content of the slag could be arrived at by utilising high manganese pig iron (spiegeleisen) or by adding manganese ore or oxide to the slag. The use of limestone depends on the fact that calcium oxide can displace iron oxide from a silicate slag; one such reaction could be

$$2CaO + Fe_2SiO_4 = Ca_2SiO_4 + 2FeO$$

The iron oxide is released to perform further oxidation, but the slag thereby loses some of its potential for oxidation since its iron oxide content is lowered.

2 The addition of any material containing appreciable amounts of silicon and manganese is effective in the presence of sufficient carbon. Later practice was to add both ferrosilicon (an alloy with about 45% silicon and 55% iron) and ferromanganese (generally about 80% manganese with up to 5% carbon, balance iron) to stop the reaction.

The production of larger volumes of liquid metal than had hitherto been available at any given time necessitated a mechanism for handling them and the use of a ladle, previously common practice in the cast iron founding industry, came into the steel industry to meet this need. Early Bessemer plants seem to have used direct pouring from the lip of the converter vessel. Very soon, however, a system was developed whereby the metal was poured from the converter into a ladle supported on an arm which was pivoted at its centre. To cast the metal, the ladle was rotated until the nozzle in its base was over the centre of one of the series of moulds arranged along an arc, equidistant from the pivot. The stopper device would then be opened, sufficient metal run out to fill the mould, the stopper lever used to close the nozzle, the ladle moved to the next mould, and so on.[1] As time went on, such a ladle, supported by an overhead crane with both longitudinal and cross traverse, came into general use with moulds set in casting pits, sunk into

1 Drawings of this kind of arrangement survive; such can be seen in F. W. Harbord and J. W. Hall, <u>The Metallurgy of Steel</u> (London, 1904), p.5 and Plate IV.

the floor, arranged in lines.[1]

The original Bessemer process was operated in converters lined with firebrick or silica brick; likewise the Siemens Open Hearth furnace has a roof lined with silica brick and a hearth produced by the fritting of layers of pure silica sand on top of firebricks. Both these constructions are in what are termed 'acid'

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1 Various modifications were brought in to satisfy the need for handling larger bulk of liquid steel, as the process developed, including the casting of ingots set on bogies so as to be moved under a stationary ladle. Some ladles were made oval in section, with two nozzles and stoppers for simultaneous casting of two ingots. The classical solution to the need for getting rid of metal quickly was to set a cluster of moulds around a central down runner, each mould having a central hole in the base, connected by a fireclay runner sleeve to the central one, so that clusters of four, six, eight or even a dozen ingots could be poured simultaneously in little more time than it would take to cast one ingot by the normal method. This was termed 'bottom pouring' or 'uphill casting'. It is of interest to note that this principle was quoted in British Patent No.1193, granted to William Weild on 11th May 1864. Similar principles were covered in British Patents No. 546 (1867) set out by A. L. Holley, using a large central mould connected to two smaller side moulds, which were provided with 'stoppers', whose depth could be varied, to provide ingots of the required length and weight and also to give solid ingot tops. The earliest use of a central runner with moulds arranged round in clusters, on what is now recognised practice, comes in British Patent No. 1788 (1873), granted to B. D. Healey.

refractories.[1] A feature of such linings is that they will not assist in the removal of either sulphur or phosphorus from the steel. As should now be well appreciated, both these elements are detrimental to steel quality. In the Bessemer process they tended to concentrate slightly in the liquid steel, since the losses of carbon, silicon, manganese and some iron reduced the actual weight of metal present without removing any of these two unwanted elements. In the Siemens process, whilst the bulk of metal was not greatly affected and could, in some cases, increase slightly, there could be some absorption of sulphur from the producer gas and any sulphur and phosphorus present in the iron ore would also find its way into the steel. Thus, for both processes, low sulphur and phosphorus materials, derived in the main from good quality haematite ores, were essential.

This was all changed in 1879 when Sidney Gilchrist Thomas announced his 'basic' process for the removal of

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1 'Acid' refractories, in general, are those which contain silica as a major constituent. The result of attack on them during steelmaking operations is to form 'silicate' slags, which are compounds derived from silicic acid, the silica forming the acid part of the molecule. The firebricks, derived from fireclay, are the most usual form. Ganister, or silica rock, silica sand and silica brick are almost entirely composed of silica itself and are therefore acid refractories. The use of any other refractories, apart from plumbago or graphite, was unusual up to about 1870.

phosphorus. This relied on the use of dolomite[1] for the furnace lining, together with an addition of lime to produce a basic slag, capable of holding oxidised phosphorus as calcium phosphate and sulphur as calcium sulphide, thus allowing the removal of both these unwanted impurities. The method was first applied to the Bessemer converter to give a method which was referred to in this country as the 'Basic Bessemer' process but which was always known on the Continent as the 'Thomas' process. Within a few years, the same principles were applied to the Siemens Open Hearth process. Paradoxically, all these three major inventions, those of Bessemer, Siemens and Thomas, were made in this country but their joint effect was to open up the whole of the iron ores of the world, most of them phosphoric in character, to the steelmaker and, within fifteen years of Thomas's discovery, both America and Germany had outstripped Britain, which had been the major steelmaking nation for at least a hundred years.

This, briefly, was the overall picture of the

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1 Dolomite is the naturally occurring double carbonate of calcium and magnesium, $CaCO_3.MgCO_3$. On ignition it gives a mixture of the two oxides lime (calcium oxide, CaO) and magnesia (magnesium oxide, MgO). These materials are the 'basic' refractories, combining with silica to produce silicates where the lime or magnesia form the basic part of the molecule. Phosphorus, oxidised to the pentoxide, can form stable calcium phosphate.

development of steelmaking at this critical period of its development. The further detail which follows on the three crucial inventions and their individual early development will illustrate a fascinating divergence of background and outlook between the various inventors.

VI Bessemer's Pneumatic Process

Bessemer may best be described as a professional inventor[1] who became interested in the improvement of wrought iron, for the production of ordnance, and tried blowing air into a puddling furnace to try to speed up the process. He did not succeed in his aim but was sufficiently observant to note that some scraps of pig iron on the furnace banks had decarburised almost completely. He then had the notion of investigating the effect of blowing air through molten pig iron into a crucible. The resulting volcano of action quite terrified him, but he found the product was 'liquid

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1 Over the period 1838 to 1883, Bessemer filed no less than 116 patents. Of these, 44 related to iron and steel, 14 to the making of ordnance, 13 to the refining of sugar and the remainder to a wide variety of items from the production of velvet to the making of telescope lenses.

wrought iron'[1] free from entrapped slaggy matter. The scaling up of such a method from 40 lb. in a crucible to 7 cwt. in a 'converter' took him only three months and it was at this stage that he was persuaded to give his news to the world. Thus, on 13th August 1856 he read his report on 'The Manufacture of Malleable Iron without Fuel' to the meeting of the British Association at Cheltenham. It should be noted that the idea of applying it to the manufacture of steel came almost as an afterthought and Bessemer only considered that a 'semi-steel' could be envisaged at the time of the Cheltenham meeting.[2] The manufacture of steel by the process was only to follow after some years of frustration. As Brearley stated :[3]

> 'Bessemer, who was not a steelmaker, conceived an idea which would never have entered a steelmaker's head. The idea worked, but it was an amazing piece of indiscretion to assume that it would lead to anything but failure'.

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1 This was later to be known as 'mild steel'. A full description of this experimental work is to be found in H. Bessemer, An Autobiography (London, 1905), pp. 138-151, together with details of early commercial plant as set up in his Sheffield works.

2 The complete text of the paper may be found in the Autobiography (pp.156-161). It was published in The Times on 14th August 1856. Due to the subsequent disasters to the early licensees, however, it was not thought prudent by the British Association to record it in the records of the Cheltenham meeting.

3 H. Brearley, Steel Makers (London, 1933), p.121.

Meanwhile, however, within a month of the announcement he had received royalties of £27,000 from the ironworks of Dowlais, Butterley, Govan and a Welsh tinplate works. Then disaster struck; one by one the licensees made their trials and each made an unforgeable, useless product. Bessemer, who confessed he knew little of metallurgy and no chemistry, paid them back their fees. Robert Forrester Mushet, down in the Forest of Dean, was both a metallurgist and a chemist of no mean repute; he took some of the useless product, which he recognised as being over-oxidised, melted it in a crucible and added spiegeleisen, cast an ingot and forged the product. He also blew metal in a converter, treated it with spiegeleisen and again made perfectly good material. There were other problems still to be solved, particularly when it came to the wider application of the process to steelmaking. Bessemer, quite fortuitously, had carried out his original trials on remelted pig iron from Blaenavon, which was a haematite iron, low in phosphorus.[1] The embrittling effect of phosphorus is not too noticeable in the absence of carbon, but with as little as 0.25% carbon present can

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1 It should be remarked that Mushet's experiments were also likely to have been carried out on similar materials in the Forest of Dean. Certainly, there were two problems which Bessemer had to combat; over-oxidation, which would certainly be cured by recarburising by means of spiegeleisen, and the presence of phosphorus, which was not to be cured in this way.

be catastrophic. Not knowing what the problem was, Bessemer got together a team of advisers, headed by Dr. John Percy, who by the application of the new tool of chemical analysis eventually elucidated that phosphorus was, indeed, the source of the trouble. Low phosphorus ores in this country were indeed scarce, confined to the Forest of Dean, the Furness-Cumberland area and Weardale. Bessemer therefore obtained some pig iron from Workington, made from the Cumberland ore and therefore expected to be low in phosphorus. The trials with this material were again a failure; chemical analysis showed the product to contain excessive amounts of phosphorus. Bessemer went to Workington to investigate; the red material used as 'flux' in the blast furnace turned out to be 'puddling cinder', brought up from Staffordshire as ballast on return journeys from ore delivery and containing upwards of 5% phosphoric oxide. Substitution of local coal measure shale as flux gave a good, low phosphorus pig iron which converted to good steel in Bessemer's furnace.

Having sorted out his metallurgical problems, he now had a credibility problem. After some months of frustration, he decided to come to the heartland of the steel industry and set up his own works in Sheffield.[1] After two preparatory years, the Sheffield works was a great success. Meanwhile, in Sweden, an early success with the process had been achieved at Edsken by Goran Fredrik Goransson. The original licence, taken out in 1857, included instructions as to how to construct a suitable furnace: the first furnace, built to Bessemer's specification, gave little success. Goransson thereupon modified the tuyere design to let in more air but at a lower pressure, quite against Bessemer's advice, and immediately obtained fluid metal, free from slag, and, as Goransson himself stated later :[2]

> '.... from this date the Bessemer method can be regarded as having started'.

This was on 18th July 1858. He later sent 15 tons of ingots to Bessemer's new Sheffield works and Bessemer was elated at the quality of the product when they were forged.

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1 These were situated in Carlisle Street. The office block, still known as 'Bessemer Building' (and carrying the date 1856, although it was not erected until 1859) is now occupied by Firth Brown Tools Ltd. The Bessemer Works, opposite, stood on land now carrying a Firth Brown machine shop, which, nevertheless, is referred to as 'Bessemer Department' to this day.

2 This appears in a letter written 6th November 1879 from Goransson to Professor Richard Akermann of Stockholm. The text is reprinted in E. F. Lange, 'Bessemer, Goransson and Mushet; A Contribution to Technical History', Manchester Memoirs, vol.lvii (1913), No.17, p.14.

Strangely enough, Bessemer's autobiography makes no mention of Goransson, although it is patently obvious that he gained much from the Swedish experience, even to the use of high manganese pig iron from Sweden and the practice of 'catching the carbon'.[1] This obviously avoided all the pitfalls of overoxidation. Prior to this, Bessemer had been granulating the product from his converter by pouring it into water, prior to remelting it in crucibles with additions of charcoal, Swedish white iron or spiegeleisen so as to produce tool steel to compete with the Sheffield steelmakers. The statement in his partner's note book in 1859[2]

'.... first made steel direct.'

is a significant one. Goransson did not add any spiegeleisen, there being sufficient manganese retained in their particular process. This fact was used by Bessemer in his dispute with Mushet; he also claimed that the Sheffield steelmakers had been adding manganese to their

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1 'Catching the carbon' implied stopping the blow whilst the carbon was still being oxidised so as to leave the required amount in the metal. This was in contrast to the method of blowing out all the carbon, thereby also removing all the silicon and manganese and producing some free oxygen in the metal, which was then 'rotten' or 'burnt' or 'overoxidised' unless some 'deoxidation', such as the addition of spiegeleisen or ferrosilicon and ferromanganese, were applied.

2 Diary entry by W. D. Allen, 18th June 1859, as reported by Lange, loc.cit., p.17.

charges since 1839 and that he was merely following custom and practice. Mushet, on the other hand, argued that he had pointed the way for Bessemer's success based on his own metallurgical experience. Bessemer denied the validity of the argument but thought fit to grant Mushet a pension.[1]

Meanwhile Bessemer's activities in their midst gradually persuaded the Sheffield steelmakers to take out licences - John Brown in 1860, Charles Cammell in 1861 and Samuel Fox in 1862 - and between them they proceeded to build up a new branch of the industry, largely based on the production of steel railway rails, whilst still retaining their interest in the old Sheffield processes. Converters began to be erected across the country, many in established steelworks, some on new sites, such as Cammell's installation at Penistone, but none were quite as noteworthy as the group at the Barrow Haematite Steel Company. Logically, of course, with a plentiful supply of low phosphorus haematite ore to hand, it would be natural to establish a Bessemer works in this area; what was fascinating, however, was the rate of growth. From a vacant site in 1863, it had eleven blast furnaces, each producing 4500 tons of 'Bessemer Pig' per annum, by 1867. By 1872

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1 F. M. Osborn, The Story of the Mushets (London, 1952) pp.38-48, 66-68, 136-154. Mushet himself claimed with some justification that the process should be considered as the Bessemer-Mushet process.

it had six 5-ton converters and twelve 7-ton converters; by 1880 it was producing 150,000 tons of steel in the year, about an eighth of the British total, and the population of the town had quadrupled in 17 years. It was the largest steelmaking plant in the world, for a short period. Nearby, at Workington, the West Cumberland Iron Company decided to enter the steel business and set up four 7½-ton converters and in 1874 was making 2000 tons of steel a week and employing 2500 workers.[1]

By 1879, almost a million tons of steel per annum was produced in this country alone by Bessemer's process - so much that haematite ores had to be imported to supplement the Cumberland and Furness sources. Indeed, John Brown of Sheffield, in the early 1870s, purchased an iron ore mine in Spain and, in the middle of his steelworks, erected a blast furnace to smelt these ores. There is also a tradition that he also built a smaller blast furnace to produce his own ferromanganese and so make his extensive Bessemer plant self-sufficient.

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1 For the full history of Bessemer steelmaking in this area, which was the location of the last operations of this type in the country in 1974, giving over a century of Bessemer blowing, the reader is referred to J. Y. Lancaster and D. R. Wattleworth, The Iron and Steel Industry of West Cumberland (Workington, 1977).

VII Siemens and the Open Hearth Process

Whereas Bessemer was a self taught entrepreneur, William Siemens was a fully trained engineer.[1] Whilst his prowess in the field of steelmaking, however, was based on the use of the regenerative furnace, it seems that the original idea came from his brother Frederick, as set out in an 1856 patent :[2]

> 'The heat of the products of combustion is abstracted by passing the same through chambers containing refractory materials, so arranged as to present extensive heat absorbing surfaces, and is communicated to currents of air or other gases by passing the latter currents alternately over the same heated surfaces and in the opposite direction to that in which the products of combustion have recently passed'.

The two brothers worked together with the aim of producing a furnace which was applicable on a fully commercial scale and two furnaces were erected in 1857, one at the

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1 Charles William Siemens was trained in mechanical sciences at the University of Gottingen and then apprenticed to an engine maker. The major activity in his early career was in the design of furnaces and his initial successes were in the glass industry. Having moved on into the metallurgical field and particularly into the iron and steel industry, he later turned his attention to electric power generation and transmission. Like Bessemer, he took out over a hundred patents on a wide variety of subjects.

2 British Patent No.2861, 2nd December 1856.

works of Marriott and Atkinson in Sheffield[1] and the other at Lloyd and Fosters works at Wednesbury, this latter quite definitely being for reheating iron and steel billets for rerolling. The earliest recorded success in the application of the regenerative principle to steel-making appears to have been at the Brades works where crucible steel was melted in 1861.[2]

Siemens had many ideas on steelmaking which he wished to investigate and in 1865 he took over a small works in Birmingham. By August 1866, he reported a five week campaign, making soft steel for wire, at a cost less than Bessemer's and of superior quality, the lining of the furnace still being intact.[3]

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1 There is some confusion as to the purpose of this furnace but a later reference seems to make it clear that its purpose was the same as that at Lloyd and Fosters, namely the reheating of billet (C. W. Siemens, 'On a Regenerative Gas Furnace ...', Proc.Inst.Mech.Eng. (1862), p.42). On the other hand, there are references to trials of steelmelting in Sheffield which failed 'in the inventor's view, partly on account of defects in the early furnaces and also, in great measure, from the want of perseverance on the part of the manufacturers and their workmen' (J. C. Carr and W. Taplin, A History of the British Steel Industry (Oxford, 1962), p.33). The site of these experiments is not recorded but one authority suggests they were at the works of Marriott and Atkinson (W. Pole, The Life of Sir William Siemens (London, 1888), p.102).

2 C. W. Siemens, Proc.Inst.Mech.Eng. (1862), p.34. This paper also includes drawings of such a furnace (Plates 18 to 21).

3 Pole, loc.cit., p.147.

In 1867, he extended the works and added new furnaces, now referring to his establishment as 'The Siemens Sample Steel Works', and it was then that the true 'Siemens Open Hearth Process'[1] was developed. A year later he moved to larger premises in South Wales, setting up the Landore Siemens Steel Company. By mid-1869 he was producing steel at the rate of 75 tons per week and a description of the operations at Landore[2] makes it quite clear that this was, indeed, the process which was to carry his name for three quarters of a century. Expansion at Landore continued: 100 tons per week by 1870 to 1000 tons per week by 1873. By this time Siemens steel had gained a reputation for quality and in due course it received Admiralty approval for its application to ship plate after the most stringent tests. By this time, steel manufacturers were becoming interested and the first commercial plant was set up at Hallside, near Glasgow, in 1873.[3] The Works Manager at this plant, J. Riley,

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1 Also referred to as 'The Pig and Ore Process', as distinct from the 'Siemens Martin Process' or 'The Pig and Scrap Process'.

2 C. W. Siemens, 'On Smelting Iron and Steel', Jour.Chem. Soc., (1873), pp.661-678.

3 The origin of the Hallside Works has already been mentioned. It may be remembered that they were commenced to operate the Siemens direct reduction process on the accumulation of iron oxide, produced as a by-product from the chemical industry. It was then found that the furnaces worked well on the pig and scrap process but that the results were variable. They then changed to the true 'Siemens' process, all this within a very short period, certainly less than a year.

reported on the process which came into use at Hallside in the following words :[1]

> 'The charge consists mainly or entirely of pig iron, which is placed on the bottom or round the sides of the furnace. Melting requires four or five hours; then ore of pure character is charged cold into the bath, at first in quantities of four or five hundredweights at a time. Immediately this is done a violent ebullition takes place; when this has abated, a new supply of ore is thrown in, the object being to keep up uniform ebullition. Care is taken that the temperature of the furnace is maintained so as to keep the bath of metal and slag sufficiently fluid; but after the lapse of some time, when the ore is thoroughly heated and reduction is taking place rapidly, the gas may in part be shut off the furnace, the combustion of the carbon in the bath itself keeping up the temperature. In the course of the operation the quantity of ore charged is gradually reduced and samples are taken from time to time of both metal and slag; when these are satisfactory, spiegeleisen or ferro-manganese are added and the charge is cast. This mode of working has this advantage, that there is greater certainty as to the result because of the known composition of the materials charged which cannot be the case in dealing with large quantities of scrap, obtained as it may be from a thousand sources'.

In due course, as chemical analysis and other means for checking the carbon content of the metal in the furnace became more widespread, the incorporation of fair quantities of scrap, possibly up to 50% of the charge on occasion, when the quality of the scrap was known, became the general rule. The process gained in importance with the growth of the forging trade and furnaces of this type were installed by all the large Sheffield steelmakers in the 1880s and were to

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1 This report is quoted in W. T. Jeans, The Creators of the Age of Steel (London, 1885), pp.159-160.

operate until after the Second World War.

VIII The Solution to the Phosphorus Problem

The problems which had dogged Bessemer with regard to phosphorus did not trouble Siemens, since he had the benefit of coming to the steelmaking scene when the role of phosphorus had been elucidated; he worked in acid lined furnaces but carefully used low phosphorus materials.

There still remained a need, obviously, for a process which would allow pig iron from highly phosphoric ores to be used for stelmaking if such a procedure could be achieved; the more so since the greater majority of the world's iron ores are phosphoric. It would seem that as early as 1830 successful attempts were made to dephosphorise such metal by lining a puddling furnace with an iron rich dolomite at Kladno in Bohemia.[1] The patent literature, from about 1855 onwards, abounds with proposals for eliminating phosphorus from steel. It seems fair comment, however, that many of these were clearly impracticable, being the application of various unlikely 'physics', whilst the rest were doomed to failure because of the inevitable attack on

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1 This fact and a number of other references to early French work are derived from a history of the basic steelmaking processes by L. Guillet, Revue de Métallurgie, Mémoires, vol.14 (1917), pp.1-38, abstracted in J.I.S.I. (1918), vol.XCVIII, p.470.

the furnace linings of the time. It was gradually appreciated that a basic or 'limey' slag was essential if the oxidised phosphorus was to be retained in the slag and not revert to the metal, and Gruner pointed out, as early as 1857, that a slag with less than 40% silica (and preferably less than 30%) was essential for this purpose and that a furnace lining rich in basic oxides would therefore be necessary. Siemens tried bauxite[1] as a refractory to contain basic slags but this suffered badly. Gruner's further researches led him to propose the use of dolomite as a lining material in 1867, but the most original work seems to have been carried out by Emile Muller, who proposed magnesia linings for both Bessemer and Siemens furnaces.[2] Using pure magnesia, made into bricks at his works at Ivry, he sought means to eliminate sulphur and, particularly, phosphorus from molten steel. The onset of the 1870 Franco-Prussian war, however, put a stop to the work of both Gruner and Muller. The most serious work on a basic lining material prior to the eventual success of Gilchrist Thomas was also destined to be put on one side. George Snelus, working in South Wales in 1870, came to the conclusion that a hard burned lime might just be practicable as a furnace lining: it worked on a laboratory scale. His further work indicated that magnesian limestone

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1 Bauxite is a naturally occurring form of aluminium oxide. This oxide can act either as an acid or a base, depending on the circumstances. In the presence of silica and iron oxide, it forms quite fluid slag.

2 French Patent No.84735, 1869. It seems a parallel patent was taken out in this country (British Patent No. 908, 1869, in the name of J. H. Johnson, acting as agent for Muller).

(or dolomite) was superior to a straight calcium limestone and in 1872 he took out a patent covering the use of hard burned magnesian limestone with a small amount of iron oxide as flux.[1] He then changed his employment, going to the West Cumberland Works and, whilst he carried on his experiments in a somewhat desultory fashion, it was hardly proper of him to try to convince the world outside that haematite ores were not really essential for steel production and that phosphorus could be forgotten if certain suitable precautions were observed. He did reveal to the world in 1879, however, that he had carried out successful trials some years before :[2]

> 'Following these conclusions I made several blows in a small 2 cwt. converter soon after I went to the West Cumberland Works. The results of these experiments I have shown to many private friends and I now have pleasure to lay the details before the Iron and Steel Institute ....
>
> I have pleasure to place before the meeting what I believe to be the first sample of Bessemer steel made entirely from Cleveland ore by one operation in which the phosphorus has been reduced to a mere trace. A portion has been forged into a chisel, while a rough portion of the same still has part of the lime lining attached to it. With the samples I have placed the original wrapper bearing the date when the sample was made and also my note book with the original entries of the details of the analysis'.

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1 British Patent No.908, 24th June 1872.

2 G. Snelus, 'On the Removal of Phosphorus and Sulphur during the Bessemer and Siemens Martin Processes of Steel Manufacture', J.I.S.I. (1879), Part I, pp. 135-143.

Meanwhile, the problem of phosphorus was exercising the minds of many authorities in the steel world, among them Krupp in Germany and Lowthian Bell in this country; both achieved limited success by the use of slags high in iron oxide and low in silica. Such was Bell's stature in metallurgical circles that his repeated failure to find a solution tended to the opinion that the problem was indeed insoluble. He presented two papers to the Iron and Steel Institute on the reactions in the puddling furnace and in the Bessemer Converter in 1877. A further paper presented at the Spring Meeting of the Institute in 1878[1] showed his researches were foundering. It is the discussion to the paper which is of historical importance, however, Professor Williamson enquired whether Mr. Bell had considered that some benefit might be obtained by replacing some of the iron oxide in the slag by a non-reducible basic oxide, such as lime or some other base of comparatively little value. At this, George Snelus informed the meeting that he had, some years previously, taken out a patent covering the use of lime as a steelmaking refractory and that the patent was still valid. One of the youngest members present, a Mr. Sidney Thomas,

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1 I. Lowthian Bell, 'On the Separation of Phosphorus from Pig Iron', J.I.S.I. (1878), Part I, pp.17-34; Discussion pp.34-47.

stated that he had succeeded in eliminating phosphorus almost completely from the metal in a Bessemer converter; he believed that the practical difficulties in the way had been overcome and that Cleveland pig might be made into good steel without any intermediate process. Lowthian Bell's reply to the discussion included an acknowledgement of Professor Williamson's comments, indicating that he was, indeed, trying the addition of lime but that his tests were not yet in a sufficiently advanced state to enable him to deal with that matter at present; he seems to have ignored the comment from George Snelus. His next comment was as follows :

> 'With regard to what Mr. Sidney Thomas hoped to do with the Bessemer converter, he was so much interested in freeing iron, and particularly Cleveland iron, from phosphorus, that he should hail as a public benefactor any gentleman who would come forward and do the work more perfectly and more economically than he had been able to effect this object himself'.

Sidney Gilchrist Thomas was neither a professional inventor like Bessemer or a trained engineer like Siemens. An apt description was that :[1]

> 'He was one of the last and perhaps the most important of the line of tinkerers that had made the Industrial Revolution. After him, the professionals just about had the field to themselves'.

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1 Landes, loc.cit., pp.258-259.

He was, in fact, a police clerk, but one with an enquiring mind who went to evening classes to study chemistry. There he became acquainted with the problem of phosphorus in steel and, having learned from Professor Chaloner that the man who eliminated it in the Bessemer converter would make his fortune, gave the matter his ever increasing attention. His cousin, Percy Carlisle Gilchrist, was a steelworks chemist and in 1877, having moved to Blaenavon, found himself able to carry out experimental work. The two cousins collaborated in small scale trials with limestone bricks and lime additions in a 6 lb. converter, working on a Northampton pig iron with 1.5% phosphorus, Thomas travelling to Wales every weekend over a period of nine months. The results were sufficiently encouraging for E. P. Martin, the works manager at Blaenavon, to provide facilities for larger scale experimentation. The first trials on a half-ton scale were eminently satisfactory but those subsequently carried out at nearby Dowlais on a full five-ton vessel failed due to the unsatisfactory nature of the basic bricks. It was at this stage that Thomas prepared a paper for the Paris meeting of the Iron and Steel Institute in September 1878; presentation of this paper was excluded by pressure of other business, the French contributors being given priority. Windsor Richards, manager of Bolckow, Vaughan and Company in Middlesbrough, however, read the paper and in October visited Blaenavon to persuade the two cousins to work with him in Middlesbrough, providing two 30 cwt. converters and facilities for brickmaking. This latter feature was crucial and several months work was needed to provide suitable lining blocks by using hard fired dolomite bonded with coal tar. When Thomas eventually was allowed to present his paper in May 1879 he was able to provide an addendum giving details of successful commercial operations from 4th April onwards at the Eston Works.[1]

He was immediately besieged by those wishing to take out licences, particularly the Continental companies who had access to phosphoric ores. The Basic Bessemer Process, as it was termed, had no such problems as had bedevilled the Acid Bessemer Process. In addition, a basic lining of the same type, operating with basic slag, could be used in the Open Hearth furnace. This seems to have been tried first at the Brymbo Works in North Wales in 1884 and then on a large scale at Frodingham in 1888.

The future of steelmaking in this country and, particularly, abroad had been radically changed. The chief beneficiaries of the Thomas invention, without any doubt, were the United States and Germany. Other

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1 S. G. Thomas and P. C. Gilchrist, 'On the Elimination of Phosphorus', J.I.S.I. (1879), Part I, pp.120-134.

processes have been developed over the last hundred years and both the Bessemer and the Open Hearth processes are now extinct. The interplay between the various methods over the intervening years is not part of this discussion but some idea of the picture can be seen in Figure 31.

10 THE CHANGING SCENE: THE NEED FOR BETTER STEEL

> 'The subject was new and opened into a large and interesting field. Almost an infinity of different metallic combinations may be made according to the nature and relative proportions of metals capable of being alloyed. It has never been shown by experiment whether pure iron when combined with a minute portion of carbon constitutes the very best material for making edge tools'.
>
> Stodart and Faraday, 1820

I An Introduction to Alloy Steel

The concept of an 'alloy steel' may be viewed in the light of normal alloy manufacture, whereby two or more metals are combined by fusion to produce a material with properties which render it more suitable than either of its constituents for some specific purpose. For examples, the two relatively soft metals, copper and tin, when melted together in suitable proportions, will produce bronzes which are durable, useful materials.

Steel in its simplest form, and indeed the only form in which it was generally produced until the latter years of the nineteenth century, having been demonstrated itself to be an alloy of iron and carbon, could also conceivably be improved by the addition of alloying elements. There are traditions, of course, that the famous sword blades of

Damascus and Toledo contained constituents such as nickel, tungsten and other metals and early implements seem to have been made from iron-nickel alloys of meteoric origin. It is important at this stage, however, to note the 'incidental' constituents of steel, such as small quantities of sulphur, phosphorus, arsenic and so on, derived in general from the iron ore, and also those small, but deliberate additions, such as silicon, manganese and aluminium, whose function is to render the steel sound in the ingot, usually termed 'deoxidisers', or the manganese added to neutralise the harmful effects of sulphur. These are not alloying additions as is generally understood. One definition of alloy steel reads :[1]

> 'An alloy steel is one which contains one or more elements other than iron and carbon in sufficient proportion to modify and improve substantially some of its useful properties'.

This seems to be a satisfactory basis for a consideration of the history of such materials.

II Early Developments: The Work of Faraday and Others

The earliest attempt to alloy other metals with iron and carbon to produce alloy steel is usually considered to

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1 H. C. Carpenter, 'Alloy Steels: Their Manufacture, Properties and Uses', Jour. Royal Society of Arts (1928), Vol.76, pp.250-271.

be the work of Faraday, between 1819 and 1825.[1] Faraday's original aims were to reproduce 'Damascene steel' and to synthesise 'Meteoric steel'; this later developed into a search for a more corrosion resistant material.

It seems, however, that he was anticipated in his researches by a few years and that, as in a number of other instances, the pioneer was Johann Conrad Fischer of Schaffhausen in Switzerland. Fischer had produced a 'yellow steel' from three parts of steel and one part of copper, which he used for the making of medals, as early as 1814,[2] whilst a steel with one-fivehundredth part of silver followed in 1817.[3] When Fischer came to London in 1825, he made a point of visiting Faraday, whose researches he had obviously read, bringing with him a sample of his 'Meteor Steel', which contained both nickel

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1 J. Stodart and M. Faraday, 'Experiments on the Alloys of Steel', Quarterly Journal of Science, Literature and the Arts (1820), vol.v, pp.319-330; J. Stodart and M. Faraday, 'On the Alloys of Steel', Phil.Trans.Royal Soc. (1822), vol.112, pp.253-270. The whole of the work carried out by Faraday on alloy steel is dealt with fully by R. A. Hadfield, Faraday and his Metallurgical Researches (London, 1931). This volume also covers the detailed examination carried out by its author on the samples left by Faraday.

2 J. C. Fischer, Tagebucher (Collected edition, Schaffhausen, 1951), pp.71-72.

3 L. W. Gilbert, 'Einige Versuche uber Legierungen des Stahls', Annalen der Physik und der Physikalischen Chemie, vol.lxix (1821), pp.257-263. Perrier, a Genevan cutler, made highly successful knives and razors from this steel.

and silver. The details of its production were vouchsafed to Fischer's London agent, John Martineau, who took out a patent to cover its production.[1] It also seems clear that Fischer produced a steel containing one seventieth its weight of chromium.[2]

Faraday's work, nevertheless, was more fully reported and is obviously better known in this country. For his time, considering also the many manipulative problems and his lack of investigational and analytical techniques, his experiments with steel alloyed with nickel, chromium, copper, silver, gold, platinum and rhodium are fascinating, particularly in that he was, in general, adding more noble metals than iron in his search for increased resistance to corrosion. That the series of alloying elements is rather a strange collection, as judged by modern alloy steelmaking, could, of course, be at least partly explained by the fact that, in the early nineteenth century, most of the modern range of alloys, silicon, manganese, tungsten, molybdenum, vanadium and so on, were virtually unobtainable; even nickel and chromium were probably just as rare as

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1 British Patent No.5259, 6th October 1825. Details of the specification may be consulted in Appendix VV. A razor made from Meteor Steel by Ebenezer Rhodes, a Sheffield smith, on behalf of Fischer in 1825, was rated by him as being very satisfactory.

2 W. O. Henderson, J. C. Fischer and his Diary (London, 1966), p.10.

platinum or rhodium. These latter two were obviously available to Faraday through his friendship with Dr. Wollaston who had been working on the platinum group metals for many years.

Faraday's experimental work was first carried out in a small furnace at the Royal Institution in London.[1] From this work, which produced buttons of steel only a few ounces in weight, he considered that the rhodium steel was the most promising:[2]

> 'One and a half per cent of rhodium was combined with the steel. The alloy was very malleable, harder than ordinary steel and made excellent instruments. In hardening these instruments it was necessary to heat them at least 70^{o}F higher than necessary for the best cast steel ... Razors made with this steel cut very admirably'.

Alloying with silver caused some difficulties due to the separation of the two metals, due to the low solubility of silver in iron :[2]

> 'When we arrived at one five hundredth we found the whole of the silver present remained in combination with the steel. The alloy was excellent; all the cutting instruments we made from it were of the best quality and the metal could be worked without fissures occurring and with remarkable density and malleability'.

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1 The description of this furnace and its use may be found in Hadfield, loc.cit., pp.99-106.

2 Letter from M. Faraday to Prof. G. de la Rive, 26th June 1820, quoted by Hadfield, loc.cit., p.123.

With regard to platinum, he did not find any advantages and found his nickel alloys were more oxidisable than pure steel. He made only two trials with chromium, at around 1% and 3% respectively, and found them easy to work, but did not examine their cutting properties.

Following on this work, some alloys were made on a commercial scale in Sheffield; these certainly included the steel alloyed with silver and also those with some of the platinum metals, particularly rhodium. The Royal Society paper gives the production details, the operations being carried out at Sanderson's works in West Street :

> 'In making the alloys on a large scale, we were under the necessity of removing our operations from London to a steel furnace in Sheffield; and being prevented by other avocations from giving personal attendance, the superintendence of the work was consequently entrusted to an intelligent and confidential agent. To him the steel, together with the alloying metals in the exact proportion, and in the most favourable state for the purpose, was forwarded, with instructions to see the whole of the metals and nothing else packed into the crucible and placed in the furnace, to attend to it while there and to suffer it to remain for some considerable time in a state of thin fusion, previous to it being poured out into the mould. The cast ingot was next, under the same superintendence, taken to the tilting mill, where it was forged into bars of a convenient size, at a temperature not higher than just to render the metal sufficiently malleable under the tilt hammer. When returned to us it was subjected to examination both mechanical and chemical, as well as compared with similar products from the laboratory. From the external appearance, as well as from the texture of the part when broken by the blow of a hammer, we were able to form a tolerably correct judgement as to its general merits; the hardness, toughness and other properties were further proved by severe

> trials, after being fashioned into some instrument or tool and properly hardened and tempered'.

There is, as a matter of some interest, an almost contemporary account of operations at these West Street works[1] which described the handling of 28 lb. charges of broken blister bar melted in crucibles of Stourbridge clay :

> 'I saw thirty (furnaces) in action, each containing two crucibles .... and the melted steel poured out, like water, into moulds in the form of ingots, about two feet long and two inches square .... to confer solidarity the ingots are conveyed to the hammering, tilting and rolling mills at Attercliffe. Here, by the power of a water wheel fifteen feet in diameter, hammers are worked weighing from 3 to 4½ hundredweight, at ten to twelve inches fall, from one hundred to two hundred and twenty times a minute. The ingots at a strong red heat are exposed to the action of these hammers .... the bars are then submitted at the same degree of heat to the tilting hammer which gives three hundred strokes a minute'.

It can be assumed that Faraday's experimental ingots were handled in the same manner. There can be no doubt that this was anything other than a most thorough investigation, limited in its scope only by the shortcomings of the facilities available. Nevertheless, not only was he competing with Fischer in this field, but Berthier,[2] in France, was also seeking out the secrets of Damascene

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1 Sir Richard Phillips, Personal Tour (1828). Other details are unknown, but the passage is quoted by G. B. Callan, Sanderson Kayser Magazine (1976), vol.2, No.9, p.13. See also Appendix WW for a later description of operations at the same works.

2 P. Berthier, 'Sur les Alliages du Chrom avec du Fer et de l'Acier', Annales de Chimie et de Physique (1822), vol.xvii, pp.55-64.

steel and made a serious study of chromium steels, with much higher chromium contents than Stodart and Faraday. He noticed the effect of increasing resistance to corrosion conferred by the presence of large amounts of chromium. Had his materials not contained so much carbon - as, of course, all true steel at the time was expected to do - he could well have anticipated Brearley, in the discovery of stainless steel, by some ninety years.

No immediate commercial development came from Berthier's work; very little, indeed, came from that of Faraday, but such as there was has left some intriguing traces. It would seem that Charles Pickslay, having read of the Faraday experiments and considering that the steel alloyed with silver could be worth introduction as a material for cutlery and for stove fronts and fenders, wrote to Faraday on 14th April 1824, informing him that he was nearing completion of his new workshops in Sheffield, where all operations could be carried out under his own supervision. The final paragraph gives an insight into the business thinking of the time :[1]

> 'Will you have the goodness to inform me if any further instructions are necessary than those published in the Repy. of Arts for jany. 1823 and where the alloys are to be obtained on the best terms and price. In return we shall have great pleasure in presenting you with fenders made of the improved steel if it succeeds to our expectation'.

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1 These letters are reproduced in Hadfield, loc.cit., pp.133-135.

Pickslay had expressed doubts as to the economics of using platinum and rhodium; nevertheless, the next communication reads as follows :

> 'Green, Pickslay and Co. have great pleasure in informing Mr. Ferrady that they have made a number of experiments with the alloys recommended by him and find the steel greatly improved by them; they send a specimen alloyed with silver, iridium and rhodium which they consider the best they have produced; these alloys with some valuable practical hints have been furnished by Mr. Johnson of 79 Hatton Garden; the report of the forgers is that the steel works better under the hammer than any they have before used and likewise hardens in a superior manner. Green, Pickslay and Co. beg Mr. Ferrady's acceptance of a pair of rasors made from this steel. They will have great pleasure in sending other specimens of cutlery as they continue their experiments'.

A further letter, dated 16th November 1826, informs Mr. Faraday that they are continuing their experiments to their own satisfaction, but to the annoyance of some of their neighbours, one of whom had marked a razor as 'Silver Steel' although it was only common steel.[1] Their 'Peruvian Steel' was being made to a secret formula :

> 'At the same time, we shall always be happy to give you confidentially any information you may wish, but, for the reason stated, you will agree with us it is not desirable

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1 It is worth commenting that the term 'silver steel' came to be applied to relatively small diameter bars, usually in the smooth ground condition, of a steel with around 0.5 to 0.8% carbon.

> to make it public. We beg your acceptance of a pair of Peruvian steel scissors, that you may judge what polish it will receive. The grinders are very much prejudiced against it, but now admit that it bears a finer colour than any other that comes to their hands'.

There is an intriguing record of a meeting of J. C. Fischer with Francis Huntsman in 1827,[1] in the forge attached to the Sanderson Works in West Street, Sheffield. Fischer found the forgeman engaged in the unsuccessful working down of an experimental ingot, which Huntsman had made from a new source of iron. 'It won't do', said Huntsman; 'I make the best steel round here and it is all made from Swedish iron of the highest quality'. Asked what he knew of Peruvian Steel, Huntsman replied that it worked rather like the ingot he had just seen. Fischer later reported that he had learned that Peruvian Steel was made by 'Bixley und Green', whereon he made his way to their premises and was courteously received by 'Herr Bixley'[2] who showed him a remarkable collection of cutlery, all made from Peruvian Steel, and then took him into the works where he was shown samples of nickel, chromium iron ore, silver, gold, platinum, borax and burned alum. With these, intimated Pickslay, was produced his Peruvian Steel, which he proudly classed as incomparable. It seems that even Huntsman could show prejudice and in

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1 Fischer, loc.cit., pp.441-442.

2 Fischer, loc.cit., pp.443-444.

this he was not alone, as is indicated by an undated notice put out by a razor manufacturer named Packwood[1] which cautions against

> '.... various unmeaning terms now in use as recommendations, such as refined steel, double refined steel, treble refined steel, Meteoric Steel[2] and Peruvian Steel ....',

whilst there is extant a rebuttal by Charles Pickslay and Company stating that, with regard to Peruvian Steel, which was made by a combination of the precious metals of Mexico and Peru with double refined steel :[3]

> '.... the celebrity this steel has attained both at home and abroad has induced some persons, by imitating the mark and by other means, to impose a spurious article on the public'.

This reference seems to have been to Adam Padley, who was formerly in the employ of Green, Pickslay and Company and was then running a works at Solly Street.[4] Charles

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1 William Fawcett Scrapbook, Sheffield City Libraries, p.94. Packwood's letter head styles him as 'Cutler to the King of England', so this document cannot be later than 1837, unless he was using old stationery!

2 One feels that Fischer would have supported Pickslay.

3 W. White, History and General Directory of Sheffield (Sheffield, 1837). The information comes from an advertisement towards the end of the directory (not paginated).

4 J. G. Timmins, The Commercial Development of the Sheffield Crucible Steel Industry, M.A. Thesis, Sheffield (1976), p.95.

Pickslay and Company went on to claim that the process was known only to themselves :

> 'The experiments by which the greatest improvements in their steel have been effected were conducted entirely by Chas Pickslay and that no one, either of the present establishment or who have formerly been connected with him or in his employ, are acquainted with the process by which it is made'.

Padley,[1] on the other hand, two years later, claimed that the process for making Peruvian steel was :

> '.... known only to himself, none of his late partners being allowed, nor any of them competent, to assist in mixing the compound for purifying the steel or sorting it for melting'.

Pickslay's firm makes its last appearance in the 1841 Directory, as, indeed, does that of Padley. So closes the evidence on one of the first tentative commercial adventures into alloy steelmaking; it should be noted, however, that it occurred in Sheffield. The only other similar venture known, that of Fischer and Meteor steel, was Swiss. Both of them, clearly, involved the crucible process.

During the next twenty years there were a few vague essays into alloy steelmaking but no commercial exploitation seems to have resulted.

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1 W. and C. Robson, Birmingham and Sheffield Directory (London, 1839), p.128.

III Mushet and 'Self Hard Steel'

Robert Forrester Mushet is normally, and with some justification, considered as the true pioneer of alloy steel making. His role in the development of the Bessemer process and his use of his 'triple compound' of iron, carbon and manganese[1] have been discussed earlier. As early as 1859, however, he had become interested in the possibility of improving tool steel by alloying it with tungsten. In the first place he reacted cast iron, melted in crucibles, with tungsten ores; later he produced a high tungsten master alloy[2]

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1 Mushet seems to have preferred to produce his own master alloy than to use 'spiegeleisen'. This was one of a series of preparations of a similar character, with a variety of elements other than manganese, including titanium, chromium and tungsten, essentially produced by melting the ore of the appropriate metal in a crucible with a pure cast iron.

2 British Patent No.100, 12th January 1859.

and melted this with a normal crucible steel charge.[1]

Strangely enough, Mushet's activities then moved away from tungsten. He set up his Titanic Steel and Iron Company at Darkhill, in the Forest of Dean, near Coleford, in 1862 and proceeded to make his Titanic Steel, a carbon tool steel made with additions of titanium. The metals so produced do not appear to have retained any titanium and cannot, therefore, be classed as alloy steels. The effect of the treatment may well, however, have been to improve the characteristics of the steel in some way, in much the same way that small additions of manganese were beneficial. Certainly, according to one report,[2] Titanic Steel was distinguished :

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1 British Patent No.101, 12th January 1859. A similar process, but also incorporating the simultaneous addition of manganese with the tungsten, appears in British Patent No.501, 24th February 1859. It should be noted, however, that there was a prior patent for the addition of tungsten to steel (British Patent No.3114, 18th December 1857, in the name of Robert Oxland - no final specification appears to have been registered) which covered the preparation of a 'wolfram metal' by fusing cast iron with tungsten ore, followed by the provision of 'superior cast steel' by melting steel with from ½% to 25% of this 'wolfram metal' according to the degree of hardness required. The communication states that ordinary steel melting pots and furnaces could be used but that the temperature should be raised to a bright white heat before pouring the steel.

2 Engineering, 27th December 1867.

> '.... by an extraordinary amount of cohesive strength. The specimens of Titanic Steel tested by transverse strains have given some of the highest figures in Dr. Fairbairn's table, both with regard to the value of the modulus of elasticity and the value of the unit of working strength. We do not know whether it be the titanium but we are assured it is Mr. Mushet's great skill as a metallurgist to which such results are due'.

During this period, Mushet took out patents on a wide range of steel treatments;[1] one which should be noted covered the simultaneous introduction of chromium and tungsten to steel.[2] The stage was now set for the introduction in 1868 of what was to be the first alloy steel of commercial importance, one which was to hold its premier place as a cutting tool material for over thirty years and was to be the forerunner of a series of tool steels which are still in everyday use. This was a steel containing upwards of 8% tungsten with up to 2% carbon and over 1% manganese, sometimes also containing small amounts of chromium, known, originally, as 'R. Mushet's Special Steel' but soon to be known as 'Self Hard Steel' and to be used world-wide.[3] The story of its discovery and its development has been told

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1 Between 1856 and 1867, Mushet took out no less than 54 patents covering various aspects of steelmaking, most of them directed towards the addition of alloy elements. An annotated list of these is to be found in F. M. Osborn, The Story of the Mushets (London, 1952), pp.126-135.

2 British Patent No.1817, 9th July 1861.

3 Strangely enough, in view of Mushet's numerous previous patents, the method of its production was kept secret and not patented, apparently on the advice of R. Woodward.

at length.[1] The technical advantage which this material had over the normal carbon tool steels was that, whilst the latter had to be quenched and tempered to give their best results, the 'Self Hard' steel would give superior results when simply allowed to cool in air from the forging temperature, although, as early as 1869, it was being recommended that heat treatment could improve it even further :[2]

> 'In its unhardened state R.M.S. is suitable for all kinds of ordinary Turning and Planing and its superiority over other steels is soon seen by increasing the speed of the lathe. But for very hard cast iron or hard steel, it may be hardened by heating the tool to redness and placing it in oil, and allowing it to remain there until nearly cold and then putting it into water until quite cold. Care must be taken, however, not to transfer the tool from the oil to the water whilst it is 'Black Hot'; it will crack if put into water in that state'.

Subsequently, it was found that even better results were obtained by reheating it to a bright red heat after forging and cooling in an air blast. This was discovered, accidentally, by Henry Gladwin about 1890; he found that tools laid down by an open door, and cooled rapidly by the draught, performed better than usual.[3] Eventually, the

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1 Osborn, loc.cit., pp.71-81, 85-95.

2 Letter to Agents from R. Woodward, Secretary of the Titanic Steel and Iron Company, 30th April 1869. Reproduced as Plate 29 in Osborn, loc.cit.

3 F. M. Osborn in discussion of F. W. Taylor, 'On the Art of Cutting Metals', Trans.Amer.Soc.Mech.Eng. (1906), vol.28, p.306.

optimum properties were determined in America, using the so-called Taylor-White process,[1] which involved the heating of the tool almost to fusion point, air blast cooling, then applying a secondary hardening procedure of heating just to redness and again air blast cooling. This discovery was followed by a gradual change from 'Self Hard' to what was, in fact, a modification of the analysis to give the range of steels which came to be known as 'High Speed Steels'.

Operations at the Titanic Works came to an end, either late in 1870 or early in 1871, and the process for the making of 'R. Mushet Special' was transferred to the Clyde Steel and Iron Works in Sheffield, run by Samuel Osborn. From 1872, therefore, R.M.S. was produced in Sheffield. There are a number of analyses of the steel produced at the Titanic Works, from two sources: a box of samples, all clearly stamped 'R. MUSHET SPECIAL: TITANIC STEEL AND IRON' analysed by Samuel Osborn and Company,[2] and two samples from the Percy Collection, analysed by the Brown-Firth Research Laboratories :[3]

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1 Taylor, loc.cit., pp.26-280; also U.S. Patent No. 668,269, 19th February 1901.

2 F. M. Osborn, The Story of the Mushets (London, 1952), p.90.

3 K. C. Barraclough and J. Kerr, 'Steel from 100 Years Ago', J.H.M.S. (1976), vol.10, Part 2, pp.70-76.

	C	Si	Mn	W	Cr	Sn	S	P
R.M.S. Samples								
No.626	1.15	0.74	1.15	10.09	nil	-	-	-
1.18" sq.	1.67	0.79	1.19	8.86	nil	-	-	-
1" sq.	1.68	0.73	1.21	9.07	nil	-	-	-
1¼" sq.	1.67	0.74	1.20	9.02	nil	-	-	-
1" sq.	1.69	0.66	1.20	8.85	nil	-	-	-
1" sq.	1.43	0.63	1.06	8.56	nil	-	-	-
Percy Samples								
3502	1.06	0.47	1.06	8.58	nil	0.60	0.063	0.042
3512	$>$1.2	0.55	1.25	8.27	nil	pres	-	0.031

A series of samples derived from the early years of the production in Sheffield are somewhat different, being higher in carbon, lower in tungsten and containing small but deliberate additions of chromium :[1]

Mark	C	Si	Mn	W	Cr
GSC	2.13	1.36	1.88	6.40	0.51
OD	2.31	0.78	1.75	6.72	0.45
CSE	2.10	1.11	1.50	6.08	0.50
NSR	2.24	1.42	1.91	6.48	0.54
ES 759	2.62		1.80	5.68	0.37
248	2.45	1.20	1.94	5.32	0.48

A sample of Mushet steel used by the Bethlehem Steel Company in America, in 1898, is still essentially the same analysis; two Bethlehem 'Self Hard' steels of the same date, however, carried substantial amounts of chromium as a replacement for the manganese in the earlier samples :[2]

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1 F. M. Osborn, The Story of the Mushets (London, 1952), p.91.

2 Taylor, loc.cit., Table 20.

	C	Si	Mn	S	P	W	Cr
Mushet	2.40	0.71	1.90	0.051	0.055	5.62	0.49
Bethlehem S.H.	1.43	0.13	0.23			8.40	1.86
Bethlehem H.S.H.	1.85	0.15	0.30	0.030	0.025	8.00	3.80

Several other steels, of both British and American origin, are listed in the same paper and show varying degrees of conservatism or experimentation as being current in the period 1893 to 1898 :[1]

	C	Si	Mn	S	P	W	Cr	Mo
Mushet Type:								
Sanderson S.H.	2.18	0.16	2.50		0.016	7.37	0.20	
Mushet	2.15	1.04	1.58			5.44	0.39	
Mushet	2.21	0.88	1.80			6.06	0.34	
Firth Sterling	2.30	0.27	3.22	0.007	0.019	7.57	0.60	
Burgess Special	2.32	0.63	3.53	0.004	0.036	7.60	0.07	
Stirling Steel	1.81	0.16	1.87	0.008	0.018	8.39	0.25	
Imperial (Park Bros.)	1.73	0.25	2.52	0.014	0.019	6.92	0.68	
Mushet Type with Increased Chromium:								
Sanderson S.H.	1.63	0.98	2.67	0.011	0.072	7.98	1.33	
Sanderson S.H.	1.84	0.89	2.43	0.007	0.023	11.59	2.69	
Sanderson S.H.	1.69	1.02	2.59		0.088	7.51	1.46	
Jonas & Colver	1.85	1.03	2.33			10.72	2.96	
Bethlehem Type:								
Sanderson S.H.	1.51	0.23	0.31	0.023	0.017	4.48	3.96	
Sanderson S.H.	1.47	0.77	0.37			6.83	3.94	
Midvale	1.39	0.36	0.32	0.022	0.016	8.48	1.46	
Midvale	1.14	0.25	0.18	0.008	0.023	7.72	1.83	
Miscellaneous:								
Atha & Illingworth	1.62	0.29	1.65	0.016	0.027		3.43	4.58

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1 Taylor, loc.cit., Table 22

This information makes it quite clear that many firms, both in Sheffield and in America,[1] were producing Self Hard steel at this time. Other contemporary evidence shows Swift Levick producing 'Clarence Self Hard'[2] reported to be

> 'highly appreciated in the metal markets'

whilst Huntsman and Company were marketing 'Ajax Self Hard'.[3]

The method of production of these steels invariably involved the use of crucible melting. For the earlier Mushet steel he seems to have reverted to his original idea of melting a cast iron with a tungsten ore. There are two main types of such ores: scheelite, which is basically a calcium tungstate, and wolframite, an iron manganese tungstate. Since the alloys are all reasonably high in manganese in the Mushet samples, it is a reasonable assumption that wolframite was, indeed, the source of both the tungsten

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1 It will be noted from these analyses that the American materials are, in general, lower in silicon content. This has implications as to the type of melting procedure used, as will be discussed later. It also, however, leads to the suggestion that some of the 'Sanderson' steels are from the American branch, the Sanderson Halcomb Works, rather than from Sheffield.

2 <u>The Century's Progress: Yorkshire Industry and Commerce</u> (London, 1893), p.129.

3 W. White, <u>General and Commercial Directory of Sheffield and Rotherham</u> (Sheffield, 1891), p.56.

and at least some of the manganese.[1] It will be noted that the earlier samples were higher in tungsten and lower in carbon than the later ones. The later Mushet samples also contained a small proportion of chromium, which could have originated in a similar manner from the incorporation of a suitable quantity of chrome ore.[2]

How long such practices persisted is not clear. Certainly the availability of scrap for inclusion in the charge would modify the process. Moreover, the majority of the samples in the above tables show such variations in composition balance that it is clear that the Mushet method,

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1 A typical reaction could be considered as

$$(Fe,Mn)WO_4 + 4C = W + (Fe,Mn) + 4CO$$

and in such case the oxidation of 1% of carbon would be accompanied by the introduction of 4% of tungsten into the steel. Thus with a 9% tungsten alloy, some 2.25% carbon would be removed and assuming that the white iron employed contained 4% carbon, this would leave a residual carbon content in the steel of around 1.75%, whilst the later 6% tungsten alloys would have a higher carbon content of around 2.5%.

2 By a similar mechanism, the chromium ore would be reduced :

$$FeCrO_4 + 4C = Fe + Cr + 4CO$$

and a 0.5% chromium addition would involve the removal of about 0.4% carbon, bringing down the carbon content of the later alloys to about 2.1%.

just discussed, must have been replaced by what would now be looked upon as normal steelmaking methods, using scrap and alloy additions. Some insight into the development can be obtained from a charge book, giving operations at the Wellmeadow Steel Works in Sheffield from 1895 to 1898.[1] Most of the output of this melting shop was for toolmaking; almost without exception this was carbon tool steel. The exceptions included a few melts of chromium steel (1.5% carbon, 1.25% chromium) for 'Special Wire'; the interest here in producing 'Self Hard' comes in 1897. The 'desired analysis' quoted is

C	Si	Mn	W	Cr
1.8%	0.6%	1.8%	10.0%	1.0%

The first melt was made on 18th May 1897 and the extract from

1 By courtesy of Geoffrey H. Peace, Esq., I have been allowed to study this volume. The Wellmeadow Steel Works was situated in Upper Allen Street in Sheffield. Its melting shop had four double crucible holes, the average charge weight being around 50 lb. The crucible holes appear to have been operated for about 180 days in the year, thus giving an ingot production of almost 100 tons per annum. It is also worth noting that this small scale operation would require well over a thousand crucibles in the year. At the same time, even though it was small scale, it had an interest in producing some alloy steel.

the charge book reads as follows :[1]

7 lb.	Swedish White Iron	4.0% = 28.0	@ 5/9	4¼d.
15 lb.	Swedish Box Ends	0.9% = 13.5	@ 8/0	1/ 1 d.
12 lb.	Swedish Blister Bar	1.0% = 12.0	@ 10/0	1/ 0¾d.
6 lb.	Nails	nil = nil	@ 4/6	2¾d.
2.5 lb.	Ferrosilicon	1.0% = 2.5	@ 4/6	1 d.
1.12 lb.	Ferromanganese	7.0% = 7.8	@ 15/0	2 d.
0.83 lb.	Ferrochromium	8.0% = 6.6	@ 1/0 (lb.)	10 d.
5.25 lb.	Tungsten	nil = nil	@ 2/0 (lb.)	10/ 6 d.
4 oz.	Charcoal	80.0% = 20.0		½d.
49.70 lb. @ 1.8% C = 89.5		90.4		14/ 4 d.
		Cost of material per cwt.		32/ 9 d.
		Melting cost per cwt.		6/ 6 d.
		Total		39/ 3 d.

No analyses are recorded, but this was quite normal. Five months

1 This requires some explanatory notes. The column with percentages gives the carbon content of the individual materials. The next column is this percentage multiplied by the weight in pounds. The prices quoted in the next column are per cwt., except in the case of the ferrochromium and the tungsten metal. Note the check of the total weight multiplied by the desired carbon content against the total figure for the individual ingredients. In the making of the normal carbon tool steel, this was the most important feature. From this charge it can be calculated that the ferromanganese contained about 80% manganese as well as 7% carbon. The chromium content of the ferrochromium, on the other hand, was around 60% and the tungsten metal was 95% pure, if the calculations of the manager were correct.

later two further melts were made with a similar charge but aiming at 1.2% chromium.[1] Four more melts of Self Hard followed a fortnight later, the last containing 25% of Self Hard scrap. On 9th March 1898, two ingots were made using a ferrotungsten, allegedly with 4% carbon and 40% tungsten; one melt was analysed and gave 4.62% tungsten only, with a silicon content around 2%. A pencil comment wryly states that the tungsten was wrong in the ferrotungsten! The next attempt shows a return to the use of tungsten metal, but again incorporating some 27% of Self Hard scrap, two ingots being produced in this way at the beginning of April. At the end of May, the records show another trial :

> 'from Blackwell's alloy using more ferrotungsten to get the tungsten up'

aiming in fact for 12% tungsten rather than the 10% sought previously. The indications are that this source of ferrotungsten was satisfactory, since on June 16th a similar heat was made, but reducing the tungsten addition back to 10%. The last information in the book, however, shows a reversal to the use of tungsten powder, four heats being made in June, two of them using scrap in the charge.

This record of small scale trials by a minor producer may or may not be typical, but it does throw a gleam of light

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1 As a matter of interest, a cast of 'Magnet Steel' was made in the interim with 0.8% carbon and 3.0% tungsten.

on what is otherwise a very shadowy picture. One interesting feature, however, is that it shows a surprising rise in the price of tungsten, over a relatively short time. It could well be that this was the reaction of the market to a sudden rise in interest in this type of material, making it worth while also for a small concern such as the Wellmeadow Works to initiate their own trials. It is significant that the price of tungsten metal rose from 2/0d. per lb. to 4/9d. per lb. in just over a year, but that the prices of ferromanganese, ferrosilicon and ferrochromium remained static.[1] The overall effect on ingot costs for Self Hard steel as quoted in these records was as follows :

28.5.97	39/3d. per cwt.
15.10.97	40/6d.
27.10.97	43/10d.
9.3.98	46/6d.
24.5.98	50/0d.
16.6.98	52/10d.
27.6.98	68/10d.

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1 The price of tungsten metal had fallen to 2/6d. per lb. by 1904 (J. M. Gledhill, 'High Speed Tool Steel', _The Engineering Review,_ 1904, pp.405-411).

The incorporation of tungsten into steel, in quantities of the order of 10%, obviously gave some problems; due to its great density and its high melting point, its efficient solution in the melt had to be carefully checked[1] and at least two of the major manufacturers saw fit to produce 'master alloys' with around 25% to 30% tungsten and some chromium. John Brown and Company were producing Self Hard steel, with about 10% tungsten and 4% chromium, between 1903 and 1905, for which they prepared crucible melts of an alloy with about 30% tungsten and 12% chromium.[2] William Jessop and Sons were doing a very similar operation between 1897 and 1901, but with a lower chromium addition.[3]

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1 This was the case even when the crucible process had been superseded by the high frequency furnace, care being taken to ensure that the tungsten was added in small quantities at a time with the furnace on full power, as I have myself seen many times.

2 This information comes from an 'Analysis Book' of John Brown and Company, now in the possession of Firth Brown Limited. This gives what seems to be a collection of 'special' or investigatory analyses carried out between 1903 and 1920. Reference to an alloy called 'mysterium' in a similar context has been made to me in a serious discussion with one old crucible man.

3 Notes were made several years ago from a number of charge books from both Jessops and Savilles and this information is based on these notes, since the records themselves appear to have been misplaced in the interim.

The metal was apparently cast into thin slabs; when cold, it was quite brittle and could be broken into suitable pieces for charging to the crucibles, and it will be noted that a dilution of two parts of iron with one part of the master alloy, in the case of the John Brown composition, would provide the necessary analysis.

There was, of course, great secrecy as to what was being done in the various works and it seems that the melters were not in all cases let into the secrets. The William Jessop instructions, given out in 1887, are completely meaningless as they stand. It seems worth reproducing them, however, despite a later hand having written the word 'Bosh' against them.

EXTRA SPECIAL HARD, MARKED C
"DOUBLE DIAMOND"

37¾ lb. DU No.5 Bar steel
20 lb. F Alloy
2¼ lb. Ferromanganese

For the preparation of F Alloy :

22 lb. Balneum
8 lb. Eisenkram
33 lb. WS 3.8% carbon

Balneum packed in paper bags, 4-5 lb. each

(a) Half the above weight Balneum charged with the metal

(b) The other half put in when metal begins to melt. Teem in old flat moulds or on floor if clean so that the preparation can easily be broken - put a little sheet scrap under stream to avoid burning through or if poured into ordinary moulds and slacked will crack up on cooling.

Alternatively, the steel could be prepared direct from the alloys, as given elsewhere in the same note book :

EXTRA SPECIAL HARD
"DOUBLE DIAMOND"

6½ lb. Balneum, parcels marked B
3¾ lb. Eisenkram, 30%, marked E
2 lb. Seidnkram, 13%, marked S
8½ lb. W.S., 3.8% C
34¾ lb. Best Blister, No.5
1¾ lb. Maniron, marked M.

1. Put in 2nd round.
2. Pots plugged and well sanded.
3. Blister at bottom.
4. W.S., E and S broken up suitable for melting on top of blister.
5. B well wrapped up in two paper bags on top of all in centre as near as possible.
6. About ½ to ¾ hour before teeming add M in a bag. Must be melted at a much stronger heat than XX.

The manager, however, had a key to all this mumbo-jumbo in his own personal note book.[1] It seems that Balneum was an impure tungsten metal with around 88% tungsten content; Eisenkram was a ferrochromium with 6% carbon and 30% chromium; Seidnkram was a 13% silicon ferrosilicon and Maniron a ferromanganese with 80% manganese and 6% carbon. DU was a medium quality Swedish iron; DU No.5 was blister steel from this iron of No.5 temper which was around 1.0-1.1% carbon. W.S. was a Swedish white iron with about 3.8% carbon. Using this information the following analyses of the products can be evaluated :

1 This also has, unfortunately, been misplaced since I made my original notes.

	C	Si	Mn	W	Cr
Alloy F	2.75			30.7	3.8
Derived Double Diamond	1.67		3.05	10.4	1.3
Direct Double Diamond	1.81	0.45	2.46	10.1	1.9

It is worth noting that a further notebook from the same source quoting charges current in 1901 was straightforwardly written, quoting a charge incorporating scrap, blister bar, chromium metal, tungsten metal and ferromanganese.

IV High Speed Steel

With the publication of the American work on metal cutting during the early years of the twentieth century, Self Hard steel was slowly replaced by the derived materials which received the name of 'High Speed Steels'. Essentially, there was a gradual reduction of the carbon level to 0.5% to 0.8%, the reduction of both silicon and manganese contents to 0.2% to 0.3%, an increase in the tungsten content to 14% or 18% or even 22% and the settling out of the chromium content at 3.5% to 5.5%. Eventually, the value of an addition of vanadium, at first around 0.3% but eventually increasing to 1.0%, as a boost to the cutting properties, was recognised and, by about 1914, the 18-4-1 High Speed (18% tungsten, 4% chromium, 1% vanadium) was firmly established as the standard high speed cutting tool material for all general purposes, with numerous variants, some containing extra tungsten and others with molybdenum and/or cobalt additions, for specific high duty applications. All these were produced in crucibles, using high quality Swedish iron and the appropriate alloys, together with suitable scrap, as available. Such records as have survived show intense activity on experimental melts and the examination of competitors' compositions. Vickers, Son and Maxim, for instance, at the River Don Works,[1] made a melt in 1903 to imitate 'Novo', a steel currently being made by Jonas and Colver, and in 1904 they were able to comment that their 'HST', with 0.6% carbon, 18% tungsten and 3.5% chromium, was

> 'superior to Novo on all tests'.

They also produced melts to the compositions of 'Osborn Mushet', 'Seebohm's Capital', 'Beardshaw's Special', 'Novo Superior' (this being one of the earliest high speed steels containing vanadium, this being in 1908) and Firth's Speedicut', and also one to

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1 This information is contained in an analysis book marked 'CRUCIBLE STEEL No.2' and 'V.S. & M.' on the spine. This gives records of experimental crucible steel melts made at the River Don Works from 1903 to 1923. It came into the author's possession quite by accident some years ago and is now lodged in the Archives of the Sheffield City Library.

'Taylor's Analysis as given in IRON AGE'[1].

Similarly, the John Brown Analysis Book covers the examination of high speed steel made by the American Crucible Steel Company, the French firm of Aubert et Duval and an unspecified German variety, as well as a multitude of domestic competitors. Meanwhile, the Atlas Works of John Brown settled down to produce 'Atlas Extra' high speed steel; during 1909 over forty analyses appear which centre on a composition of 0.5% carbon, 16% tungsten, 3.3% chromium and 0.4% vanadium. Seebohm and Dieckstahl, later to be known as Arthur Balfour Limited, were working on almost parallel lines.[2] Their records go through from 1892 to 1929; the major activity on tool steel development, however, was between 1903 and 1914 and a composition not very dissimilar to that of 'Atlas Extra' was more or less their standard by 1909. The actual analyses of a

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1 This refers to the publication of a summary of Taylor, loc.cit., which appeared in the magazine 'Iron Age'. I have not been able to trace the actual reference.

2 Note books deposited by Balfour Darwin's Ltd. with the Sheffield City Library Archives, Ref. BDR 97/1-5. These cover the experimental melts made from 1892 to 1929. One interesting point, which was brought to light during a search through these records, was that Arthur Balfour Ltd. were still making small quantities of Self Hard steel, infrequently but fairly regularly, as though to special order, right up to 1929.

selection of the steels covered by the available records can be found in Table V. One point which will appear from these analyses was that there were attempts to substitute molybdenum for tungsten in high speed steel at quite an early date, particularly in America, which had native sources of molybdenum but needed to import all its tungsten. Theoretically, the substitution of one part by weight of molybdenum for two parts by weight of tungsten was practicable, to achieve the same amount of carbide in the structure; in practice, there were some drawbacks. Nevertheless, there were trials made by most manufacturers: there was the early Self Hard by Atha and Illingworth quoted in the list of analyses above, a 6% molybdenum steel in the Vickers, Son and Maxim volume and both 6% and 9% molybdenum steels in the Seebohm and Dieckstahl records.[1]

Some valuable information on the later stages of the use of the crucible process for the production of high speed steel, in Sheffield, is given in the report of an

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1 It should be noted that tungsten shortages in the Second World War brought about the widespread use of 'substitute' high speed steels, in which molybdenum replaced either most or virtually all of the tungsten. Over the period since the war, they have almost completely displaced the 18-4-1 grade and the most commonly used high speed steel is now known as 'M2' grade, with 5% tungsten, 6% molybdenum, 4% chromium and 2% vanadium carrying about 0.7% carbon.

American observer just after the First World War.[1] This points out that, at the height of the war, some 18,000 tons of high speed steel had been produced per annum in Sheffield, all by the crucible process, a little being made in gas fired furnaces but not highly rated, and none in the electric arc furnace, which had been tried but found wanting. By 1920, production had fallen by at least 50% to 60%.

It was pointed out that supplies of tungsten had previously come largely from Germany, mostly in the form of tungsten metal powder with not more than 10% as ferro-tungsten. During the war, a firm operating under the name of High Speed Steel Alloys had been set up at Widnes for the production of ferrotungsten, and the use of the product from this source had reversed the trend. Ferrochromium was also manufactured in England, during the war, to replace the Scandinavian and Continental supplies, the major proportion coming from Newcastle Alloys Limited, who produced grades with 2% max., 1% max. and 0.75% max. carbon. Ferrovanadium had been imported mainly from America but small quantities had been smelted domestically from South African ores. The use of Swedish iron continued wherever possible, despite tests conducted by Professor Ripper at Sheffield University which showed that Armco iron, and

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1 P. M. Tyler, 'High Speed Steel Manufacture in Sheffield', The Iron Age, 10th February 1921, pp.371-374.

specially prepared pure dead soft iron of domestic origin, made equally good tools and, after the war, there was again the exclusive use of Swedish material as the melting base.

Wages in 1920 were quoted at £9 to £10 per week for melters, whilst common labour was paid £3.5.0d. to £3.10.0d. and rollers and hammermen received £4.10.0d., the comment being made that these were lower than the American rates.

Average costs in November 1920 for material to the composition

C	Mn	S	P	Cr	W	V
0.65	0.25	0.02max.	0.02max.	3.75	18.00	1.25

are given as follows :[1]

Material	Weight(lb.)	Per lb.	Cost
Tungsten metal powder	20.00	3/ 6d.	70/ 0d.
Ferrochromium, 60%	6.67	11d.	6/ 0d.
Ferrovanadium, 40%	3.00	20/ 0d.	60/ 0d.
Swedish iron	50.00	10d.	41/ 8d.
Scrap	20.33	1/ 4d.	27/ 1d.
Total metal (3% waste)	103.00		204/ 9d.
Coke @ 65/0d. per ton	350.00		10/ 0d.
Total raw materials for 100 lb. ingot			214/ 9d.
From this ingot weight some 67 lb. of sound bar plus 27 lb. scrap is obtained			
Gross material cost			214/ 9d.
Less 27 lb. scrap at 1/4d. per lb.			36/ 0d.
Nett material cost			178/ 9d.
Cost per lb. of bar (including 11d. per lb. processing			3/ 7d.

1 These costs have been recalculated in a more usual form, being expressed in an unduly complicated manner in the original.

In comparison with these calculations, it was reported that the controlled price for the 18% tungsten alloy in bar form in 1918 was 4/5d. per lb. There is also a comment that the British manufacturer was in a very reasonable position in the American market, due to the depreciation of the British currency in terms of the American dollar!

V Carbon-Tungsten Steels

Simpler tungsten steels, made by adding tungsten to the high carbon steels for use as tools, were produced at an early date in the history of alloy steelmaking. Franz Mayer at Kapfenberg in Austria is credited with having been the first to do so, having exhibited such an alloy steel at the Vienna Congress of 1858.[1] At least this procedure persisted in Austria since both the works at Eibiswald[2] and at Schloss Schondorf[3] were reported to be adding 'wolfram' or ferrotungsten to their high carbon tool steels in the last quarter of the century. A similar situation in this country was unexpectedly

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1 R. F. Bohler, 'Tool Steel Making in Styria', School of Mines Quarterly, vol.xxix (1908), pp.329-341.

2 Jernkontorets Annaler (1877), pp.71-74.

3 A. Harpf, Osterreichische Zeitschuft fur Berg und Huttenwesen, vol.xlvii (1899), pp.253-258.

revealed by the examination of some old samples in the Percy Collection.[1] One of these carried a label

'Vickers Special Steel. Secret as to Manufacture'

and was made at the Vickers River Don Works in 1869.[2] The other was a bar labelled

'O Grade Special Dannemora Cast Steel'

produced for turning and planing specially hard materials by Seebohm and Dieckstahl and supplied in 1879.[3] The analyses turned out as follows :

	C	Si	Mn	S	P	W	Sn
Vickers Special	0.62	0.28	0.24	0.060	0.029	2.64	0.13
Dannemora 'O'	1.27	0.16	0.25	0.019	0.055	3.08	pres.

As to the value of tungsten in such materials, a note

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1 Barraclough and Kerr, loc.cit., pp.73-75.

2 This was presumably the grade of steel to which reference is made in the article on the River Don Works (*Engineering*, 25th October 1867, pp.383-385) where it is termed 'beyond comparison the finest tool steel produced. It is chiefly made for their own use but is also sold at a shilling a pound and none who have once tried it will have any other'.

3 From the Seebohm and Dieckstahl records (Sheffield City Libraries, Ref. BDR 97/1), it is worth noting that this analysis subsequently became known as '6SM Grade'.

from 1881 is relevant :[1]

> 'Wilson, Hawksworth and Company use 4 lb. of pure tungsten for their Special Steel and sell it at 220/- (per cwt.).
>
> Their 'Double Extra' steel is made of half L and half GL and sells at 84/-.
>
> Their 'Extra' steel is half O O and half W.
>
> Up to 2 lb. tungsten they consider has a toughening effect on steel; above that weight brittleness tends to predominate.
>
> Half a pound tungsten added to any steel (for wire, etc.) greatly toughens it.
>
> They add tungsten in powder to the steel, placing it in the pot with the charge.
>
> The above information is from Marsden, W.H. & Co.'s late traveller'.

By inference, the weights quoted are per crucible charge of 50 to 60 lb; the addition of four pounds is thus equivalent to 7% to 8% tungsten and the price quoted leads to the suggestion that this could be another variety of Self Hard steel. 2 lb. of tungsten would thus be 3½% to 4%, and ½ lb. roughly equivalent to 1% tungsten. Jessops were in the habit of adding from 0.8% to 2% tungsten to many of their better class tool steels, particularly to their XX grade from 1886 onwards, this latter steel also containing 1.2% to 1.4% carbon. In addition, steels with about 0.7% carbon and with varying tungsten contents from 3% to 7%

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1 Seebohm and Dieckstahl Memorandum Book, Sheffield City Libraries, BDR 76. Wilson, Hawksworth and Company was the firm eventually to become Kayser, Ellison and Company.

were favoured for use as permanent magnets, showing a higher remanence than normal carbon steels.[1]

VI Chromium Steels

The activities of Faraday, Fischer and Berthier on the experimental production of chromium steels have already been discussed. The commercial production of steels containing chromium came almost as early as the use of tungsten as an alloying element. Mushet patented the addition of chromium to steel as early as 1861, and again in 1867,[2] deriving the metal by direct reduction of the ore in the crucible at the expense of some of the carbon present in the metal charge. John Baur patented the addition of chromium to steel in America in 1865[3] and manufactured a high strength steel, which he advertised as suitable for burglar proof safes,

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1 Evidence for the steels with 5% and 7% tungsten comes from the now misplaced Jessop charge book, as does that for the addition of tungsten to many tool steels. The evidence for a 3% tungsten steel for magnets is derived from the Wellmeadow Steel Works records.

2 British Patents Nos.1817, 19th July 1861, and 88, 14th January 1867.

3 U.S. Patent No. 49,495, 22nd August 1865; this covered the production of 'steel greatly improved, toughened and hardened by the addition of chromium'.

at his Chrome Steel Works in Brooklyn in 1869. What his original method was is not stated, but a report of activities at the same works over twenty years later[1] indicates that the current procedure was to melt scrap iron and such chromium steel scrap as might be available in plumbago lined German clay crucibles, together with chrome iron ore, manganese oxide, carbon and a sodium carbonate flux, the charge totalling 100 lb. Two crucibles were charged into a single hole, gas fired with regenerative checkerwork. After four hours the crucibles were drawn out, skimmed and poured; the ingots were stripped hot and charged straight to a reheating furnace. The same article reports that European practice was to use a charge of low carbon Bessemer steel, or wrought iron with cast iron, chrome iron ore and limestone. Just to confuse the issue, however, a German report,[2] from ten years earlier, states that ferrochromium was made in Brooklyn by melting finely pulverised chrome ore with charcoal in common graphite crucibles, producing an alloy with 3% carbon and 30% chromium. This was then remelted in crucibles with Swedish or bloomery iron in 70 lb. charges, using up to 2 lb. of the alloy (which would give up to 0.8% chromium in the steel), melting six rounds in a 24 hour day; it

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1 Stevens Indicator (1892), vol.9, p.49.

2 Stahl und Eisen (1882), vol.ii, p.165. This is confirmed by British Patent No. 370 (1876) taken out by Baur, which, however, also covers the direct production of steel using chrome iron ore.

appears also that the crucible holes were anthracite fired since a consumption of 2 lb. of anthracite to every 1 lb. of steel is quoted. The earliest confirmation of the use of ferrochromium in this country comes from the Jessop records of 1886.

Whatever Baur's method was, he made history by coming to the rescue of the engineers in charge of the erection of the St. Louis bridge, in 1868, by supplying his chromium steel for the staves which fitted into the outer shell on the main arch members, the original carbon steel having failed to meet the minimum elastic limit permitted. The chromium steel ingots were rolled to the required shape and were then shown to have ample reserve in strength. No analysis of the material used, however, was ever taken during the construction period and much controversy was subsequently raised on the matter. It was claimed by no less an authority than Howe,[1] one of the foremost American metallurgists of the late nineteenth century, that there was no evidence for the use of chromium, even in the slag at the works, let alone in the steel. Nevertheless, later analyses on the main arch members showed him to be in error; these indicated chromium contents of 0.54% to 0.68%, with carbon contents ranging from 0.64% to 0.96% and notably low

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1 H. M. Howe, The Metallurgy of Steel (New York, 1891), p.79.

sulphur contents of 0.006% to 0.013%.[1]

The manufacture of chromium steel in Sheffield was originated at the Atlas Works of John Brown in 1871.[2] It was used for the points of armour piercing projectiles by Firths in 1886. In 1887 a 12 inch shell pierced a 16 inch compound armour plate, which initiated a search for even better armour plate, eventually to be met by the use of even more alloy steel.[3] Chromium steel was also used for the steel tyres and springs on locomotives and tenders, particularly by the North Western Railway, and special files were produced from a steel containing 1.2% carbon and up to 3% chromium.[4] The use of chromium steel for munitions in France was taken up before 1880 by Brustlein at the Unieux Works of Holzer and Company.[5] With its more widespread use, means of obtaining it in greater quantity than could be provided by the crucible process were sought. Certainly, well before 1900, steel with up

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1 E. E. Thum, 'Alloy Steel Bridge Sixty Years Old', The Iron Age, 20th September 1928, p.684.

2 Firth Brown Limited, One Hundred Years in Steel (Sheffield, 1937), pp.10-12.

3 J. C. Carr and W. Taplin, History of the British Steel Industry (Oxford, 1962), p.134.

4 F. W. Harbord and J. W. Hall, The Metallurgy of Steel (London, 1904), p.619.

5 J. S. Jeans, Steel, Its History ... (London, 1880), pp.527-8.

to 3½% chromium was being made regularly in the Acid Open Hearth furnace in Sheffield, as it continued to be for the next sixty years.

The crucible furnaces, however, continued to provide chromium steels of various analyses, particularly when better quality ferrochromium with lower carbon began to be available. The main evidence for the interest in producing such crucible steels comes from Seebohm and Dieckstahl,[1] but there is also circumstantial evidence from the John Brown analysis book,[2] although it is by no means certain that these are all crucible melts.

Grade	Earliest Reference	C	Si	Mn	Cr
Seebohm and Dieckstahl:					
DSW	1899	1.10	3.00	0.25	3.00
SC	1900	1.95			3.90
R 62	1910	1.44	0.39	0.35	5.20
SCX4	1910	0.70			1.75
NKSD	1912	0.16			1.45
John Brown:					
Cast Steel	1904	0.93	0.47	0.32	5.40
Chrome Steel	1906	1.22		0.30	11.10
Krupp Steel	1908	0.90	0.39	0.69	1.05

As far as the production of higher chromium steels is concerned, an early patent covered an acid and weather

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1 Seebohm and Dieckstahl Note Books, Sheffield City Libraries, BDR 97/1-3.

2 There are, incidentally, a number of melts of chromium steel recorded in the Vickers, Son and Maxim volume. These quite definitely are crucible melts.

resistant alloy :[1]

> 'The alloy we prefer to use for anti-acid metal consists of 5 per cent tungsten and 95 per cent chromium combined in the proportion of 33 per cent of alloy to 67 per cent of steel. This metal is also very hard, is of a silvery colour, takes a high polish which it retains in a damp or oxidising atmosphere and is accordingly extremely useful for various purposes where high reflective qualities are required, various parts of instruments where German Silver is now used, for coinage metal and for cutlery which has to be used in contact with acids. Although the above proportions of the alloy and of its combination with steel and iron we find give good results, these proportions may be varied considerably in practice'.

No mention here is made of the carbon content and it seems almost inevitable, with the state of the art as it existed in 1872, that such materials would have been high in carbon and that their stainless characteristics would thereby have been greatly diminished compared with what we expect today. Hadfield's study of such materials also suffered from the same problem, since his alloys, produced by the crucible process, all contained over 1% carbon.[2] The realisation of the full potential of chromium additions in conferring 'stainlessness' was in fact dependent on the capability of procuring a source of chromium relatively free from carbon. Such a material, in the form of chromium metal prepared by the aluminothermic reduction of chromium oxide,

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1 British Patent No.1923, J. E. T. Woods and J. Clark, 25th June 1872. Only a provisional specification was filed.

2 R. A. Hadfield, 'Alloys of Iron and Chromium', J.I.S.I. (1892), Part I, pp.49-51.

became available on the Continent in the early years of the twentieth century and work by Guillet and Portevin in France and Monnartz in Germany[1] clearly demonstrated the resistance of low carbon steels with over 10% chromium to atmospheric oxidation and to oxidising acids.

> 'This was the position in July 1913 when Harry Brearley, having made several experimental crucible casts of high chromium steel in the course of an investigation in improved steels for rifle barrels, asked the works with which he was then associated to produce an electric furnace cast of steel with a carbon content up to 0.30% and a chromium content of 10-15%. A cast of steel was accordingly made on the 20th August 1913, the analysis of which was as follows :
>
> | | |
> |---|---|
> | Carbon | 0.24% |
> | Chromium | 12.86% |
>
> During the course of the investigations, Brearley noticed that this particular steel did not rust when exposed for considerable periods to the atmosphere of the laboratory. It was observed, moreover, that the reaction of this steel to etchants varied with the condition of heat treatment. Brearley quickly realised the possibilities of such a steel from the corrosion-resisting point of view and, in a memorandum dated 2nd October 1913, he suggested that interested firms might like to make some comparative trials. In this same note, Brearley suggested 'the materials would appear specially suited for the manufacture of spindles for gas and water meters, pistons and plungers in pumps, ventilators and valves in gas engines and,

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1 L. Guillet, Les Aciers Spéciaux (Paris, 1905), vol.2, pp.1-29; A. M. Portevin, 'Contribution to the Study of Special Ternary Steels', Carnegie Scholarship Memoirs, vol.1 (1909), pp.230-231; P. Monnartz, Metallurgie (1911), vol.8, p.161, p.193.

> perhaps, certain forms of cutlery'. Brearley persuaded a Sheffield cutlery firm to make some knives from the new steel. These knives proved successful and that was really the beginning of the stainless steel industry. It will be appreciated that his was the brain that noted its special characteristics and turned them to domestic and industrial purposes'.

The above quotation is from a report found in the archives of the Brown-Firth Research Laboratories, where Brearley himself worked; it should therefore have a certain authenticity although it is unsigned and undated.[1]

It is intriguing to note how soon a discovery in one Sheffield works was investigated by another; early in 1914, Vickers, Son and Maxim were making crucible melts of materials to Brearley's composition. For such a low carbon material - and other stainless steels which followed were preferably even lower in carbon - the crucible process was not really suitable and the production of stainless steel soon became the task of electric steelmaking, either by the electric arc furnace or the high frequency induction furnace.

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1 From its position in the particular filing box, it would appear likely that it had been produced about 1925-1930, when the details were still to be remembered by those involved.

VII Other Alloy Steels

Another important alloying element in steel is nickel. Reference has already been made to the experiments carried out by Stodart and Faraday but no commercial nickel steel was produced as a result.

Fischer's 'Meteor Steel', to which reference has already been made, contained about 0.3% nickel (together with about 0.08% silver and up to 0.2% chromium)[1] and obviously was sold, if only on a small scale. It seems that a 'Meteoric Steel', presumably Fischer's steel or a copy of it, was also being sold by a certain Herr Wolf at Schweinfurt in Germany, in 1830.[2] It is elsewhere reported that Philip Thurber exhibited several samples of nickel steel in New York in 1853, whilst Alex Parkes of Birmingham took out nickel steel patents in 1870. About the same time nickel steels were produced, experimentally, by the crucible process at Imphy in France.[3] Not until 1889, however, is there any published evidence of the production of nickel steel on any reasonable

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1. British Patent No.5259, 6th October 1825. (See Appendix VV).

2 O. Vogel, Stahl und Eisen (1895), Part II, p.718, quoting J. von Leibig, Annalen der Pharmacie (1832), vol.ii, p.237.

3 A. L. Colby, 'Nickel Steel: Its Properties and Application', Proc.Amer.Soc. Testing Materials (1903), vol.3, pp.141-168. This paper indicates that the United States was in the lead at this time in the world production of steels with 2% to 4% nickel and that France was the pioneer of the high nickel steels.

scale.[1] Hadfield, somewhat later, made extensive investigation of the effect of nickel on steel.[2] His materials were produced as 56 lb. crucible melts, making 2½" square ingots, 30 inches long. By this time, however, nickel steel had been found to have major applications in armour plate, boilers, piston rods, propellor shafts and the like. Moreover, the incorporation of nickel in steel does not present the difficulties shown by a number of the other alloying elements, since it is, in fact, less easily oxidised than iron and a full recovery of all the nickel added can be expected whatever the steel making process. The production of such steel by the Open Hearth process, therefore, was perfectly straightforward. There were some minor applications which remained with the crucible furnaces, however. One of the more interesting ones was the production of a 25% nickel steel as a material for sparking plug electrodes in the early days of the internal combustion engine. The Seebohm and Dieckstahl records cover the provision of such a material as early as 1901; the same material appears in the Vickers, Son and Maxim book.[3]

A further development in the field of the low-alloy

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1 J. Riley, 'Alloys of Iron and Nickel', J.I.S.I. (1889) Part I, pp.45-55.

2 R. A. Hadfield, 'Alloys of Iron and Nickel', Proc.Inst. Civil Eng. (1898-9), Part IV, vol.cxxviii, pp.1-125.

3 See also the comments on 36% nickel steel on p.641 and in Appendix JJJ.

engineering steels was the nickel-chromium series, usually with 2% to 4% nickel and around 1% chromium with carbon contents in the region of 0.2% to 0.5%, a group of steels with a remarkable combination of toughness and strength, when correctly heat treated. The various combinations occupy several pages in the Vickers, Son and Maxim book and they figure largely in the John Brown records; strangely enough, they are virtually absent from the Seebohm and Dieckstahl records, although it must be remembered that the latter firm specialised largely in tool steels, rather than the engineering materials which were so important to the larger forgemasters. Here again, after the development stage they passed from the crucible furnaces to the larger melting units, again in particular to the Open Hearth furnaces. At the same time, the value of a small addition of molybdenum, of the order of 0.25%, in further improving their response to heat treatment was realised; significantly, this series of alloys remains to this day as a major part of the material used in quality engineering.

That the crucible process was still considered essential in some quarters to provide the required quality even in large masses of steel, however, was evidenced by Krupps as late as the autumn of 1902, when the Iron and Steel Institute held its meeting in Dusseldorf. For the benefit of those attending, an 80 ton ingot for the production of an armour plate in nickel chromium steel was cast from 1600 crucibles, which implies that each crucible must have held a hundredweight of steel. The furnaces containing the crucibles were ranged around the casting pit. At a given signal the first crucibles were drawn out and the metal poured, the remainder following in sequence, at a rate of 94 per minute.[1]

There are two final alloy groups which should receive mention, both developed by that indefatigable investigator of alloy systems, R. A. Hadfield: the manganese steels[2] and the silicon steels.[3] These two systems provided two quite unique materials. Hadfield manganese steel with 1.0% to 1.5% carbon and 12% to 14% manganese is essentially a

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1 Carpenter, loc.cit., p.253.

2 R. A. Hadfield, 'Manganese Steel', J.I.S.I. (1888), Part II, pp.41-77.

3 R. A. Hadfield, 'Alloys of Iron and Silicon', J.I.S.I. (1889), Part II, pp.222-242.

relatively soft, non-magnetic material[1] but it hardens rapidly on application of load and is ideal for applications where wear resistance is needed, such as railway or tramway crossings, excavation buckets, digger teeth and so on. Moreover, having a relatively low melting point, it is an excellent casting material. It presented some difficulties initially, since such a high manganese material has a very erosive effect on siliceous lining materials or on clay crucible pots. It was soon realised that it could be produced in plumbago crucibles; with the advent of the electric furnaces with basic linings, however, these took over its production. Silicon steel, or, more correctly, silicon iron, since it contains only traces of carbon, with 3% to 4% of silicon, was found by Hadfield to have properties which rendered it especially useful in such applications as the sheet stampings used to build up electric

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1 The addition of the carbon and the large amount of manganese produces a structure which is termed 'austenite' at room temperatures. Normally this structure is only stable at higher temperatures, indeed, in normal carbon steels, above about 750°C, and the quenching of the carbon steel converts this to the hard form known as martensite. In the case of the manganese steel, the austenite will transform to the hard martensite on deformation, such as the application of pressure on a railway crossing, thus producing a hard wear resistant surface on a relatively ductile body. Other elements can produce a stable austenite at room temperatures, the most well known steel of such a type being the stainless 18% chromium-8% nickel steel; this, however, does not break down on application of load in the ordinary way but remains non-magnetic throughout its service life.

transformer cores, since the electromagnetic losses were thereby greatly reduced.[1] Again, its early production was in crucibles but it was soon being made in larger quantities, first by the open hearth process and then by the electric arc process.

It should now be quite evident that the growth of alloy steel manufacture, both in quantity and in complexity, was an accelerating process, particularly from about 1885 onwards, and it is, in fact, a process which has continued its momentum; only in the last few years has there been any evidence of the effort slackening. It has been a complicated discipline or, indeed, a combination of several allied disciplines, which has been needed to evaluate the best compromise to meet the numerous specific engineering requirements. Indeed, as early as 1919[2] it was stated that

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1 Hadfield himself recorded that the first experimental transformer put into service was in 1903. In 1905, it was decided to install a 40 kw. transformer with silicon steel stampings in the Sheffield City Corporation Electrical Supply Department. The core of this weighed only 830 lb. instead of 1120 for a standard transformer with pure iron stampings and the magnetising losses were only 176 watts as against 238 watts in the normal case. Moreover, whilst the normal transformer generally showed rising watt losses in service, those on the modified transformer had gradually decreased so that in 1919 they were down on the original figure by almost 40% (R. A. Hadfield, The Work and Position of the Metallurgical Chemist (London, 1921), pp.50-51).

2 H. D. Hibbard, The Manufacture and Uses of Alloy Steels (New York, 1919), Foreword.

> 'Developments in the manufacture of alloy steels and in heat treatment of steel have occurred simultaneously during the past forty years and care is needed lest the benefits gained from the one be confounded with those obtained by the other. The highest merit is obtained from the adoption of both methods together - that is, the use of heat treated alloy steels'.

The Sheffield steel industry has played its part in much of this development and, until the end of the First World War, almost the whole of the development work involved the use of the crucible process, which by then had been giving quality steel for nigh on two hundred years.

11 THE CRUCIBLE PROCESS IN BRITAIN AFTER 1800

> 'In the production of quality steel Sheffield has long had no rival .... At the time of the Great Exhibition of 1851, 86 per cent of the nation's laboriously made cast steel came from the town; today the city and district make 65 per cent of the country's so-called alloy qualities. But between the era of the small cutlery and file steel works, of firms making railway buffers, springs and tyres, and that of the great establishments famed for armour plate, ordnance, heavy forgings, of the tool steel and a host of new special steel makers, came a period when Sheffield was the world's leading producer of steel of ordinary quality. Until 1879 the district out-produced all others in Bessemer and Siemens steel tonnage, and in that year made almost half as much steel as Germany and Luxembourg and half as much again as Pittsburgh'.
>
> K. Warren, 1964

I Development in Sheffield to 1850

For the first half of the nineteenth century, the pattern of steelmaking in Sheffield was one of growth on the roots already established.[1] There were no significant technological

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1 To recapitulate, there were about a dozen establishments producing crucible steel in the Sheffield area in 1797 (J. Robinson, A Directory of Sheffield (Sheffield, 1797) lists eleven specifically as 'refiners' and at least two of the firms not categorised, John Kenyon and Son and Richard Swallow, would seem to merit addition).

changes. The actual scale of operation, however, gradually grew as a result of an increased size of crucible,[1] a proliferation in the number of melting holes and a modification of the layout of furnaces, so that each melting hole would take two crucibles instead of only one. Dependent on the demand for steel, the changes obviously came at varying dates, and in varying degree, at different establishments. There is evidence, however, that by 1842 the general pattern was of rectangular furnace holes, with two crucibles each; the typical weight of individual charge was 28 lb. to 36 lb. per crucible.[2]

A most important factor in the growth and location of Sheffield steelmaking capacity was availability of transport for raw materials and products. In the earliest phase of the crucible process, the main artery was the Don Navigation as far as Tinsley; from there to Sheffield all traffic was by road. The effect of this was to perpetuate earlier traditions in the edge tool industry in Sheffield - the steel, having been made, tended to be converted into articles of high intrinsic value, within the environs of the town, before being despatched by the expensive and inconvenient means available. The extension of the canal to the centre of the town from Tinsley, under

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1 The growth in size of crucible has been covered in Chapter 8. (See pp.279-281).

2 F. le Play, 'Rapport sur la Fabrication de l'Acier en Yorkshire ...', Annales des Mines, 4me. Serie, Tome III (1843), pp.656-657.

consideration for a considerable period,[1] only became a reality in 1819. Prior to this, most of the small steelmakers operated within the town of Sheffield and many were also cutlers or toolmakers. Two notable exceptions were Huntsman and Swallow - both being more conveniently situated for the wharf at Tinsley than most of their competitors. Walker and Booth, at Masbrough, had direct canal links to their operations and it is significant that they were the largest steel producers in the area, in the early years of the nineteenth century. In the decade after the coming of the canal to the centre of the town, three established steelmakers from within the town had erected new melting shops alongside the canal - Greaves at Sheaf Works, Jessops at Blast Lane and Marshes and Shepherd at Navigation Works.

Within twenty years of the canal extension, however, Sheffield had its first railway link with the outside world - the Sheffield and Rotherham Railway. This line left Sheffield at its extreme east end, going into open country - which had a tendency to flooding - along the valley of the Don, skirting Attercliffe and passing through Masbrough on its way to Rotherham. There, connections to Leeds and

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1 The Dunn Survey quoted earlier (Chapter 5) was a typical piece of evidence sought by those who would promote the extension; it was discussed at a meeting held at the Cutlers' Hall on 24th January 1803 which passed a resolution to the effect that 'the making of a navigable canal from Tinsley to Sheffield would be highly advantageous to the inhabitants of every description of this populous town and neighbourhood'. The steelmakers, including John Marshall, Weldon and Furness, Peter Cadman, Daniel Doncaster and Samuel Newbould, contributed to the funds for the extension. (Sheffield City Libraries, The Sheffield Canal, An Archive Teaching Unit).

London were available. Within the next quarter century, the two parallel roads alongside the first mile or so of the railway[1] carried the frontages of a number of the most famous steelworks in the town - in the world, would scarcely be an exaggeration - all with their own sidings. They had taken advantage of unbelievably cheap land[2] and moved from their cramped town quarters.

A typical example is that of the establishment of the Norfolk Works.[3] Thomas Firth, a native of Pontefract, learned his trade as a melter under Jonathon Marshall at Millsands. When Marshall ceased business in 1829, Firth went as head melter to Sandersons in West Street; he also found employment there for his two sons. In 1842, the three of them set up business for themselves, taking

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1 This is one of the earliest examples of street planning on a grid pattern. The railway is crossed by a number of bridges running across the grid; the one carrying Sutherland Street is still known as 'Cammell's Bridge' (it leads to the Cyclops Works) whilst the next one down the line, which carries Carwood Road over the railway, is 'Brown's Bridge'. This, as shown in the 1852 Ordnance Survey map, was a very narrow carriageway. Some few years ago, Firth Brown took up the railway lines and made the track into the central roadway through their works, and excavated under the bridge. It was clear that the old bridge, with relatively common building stone, had been widened very elaborately, presumably at the time when John Brown wished to improve communications between the parts of his works either side of the bridge, around 1860.

2 According to A. Birch, The Economic History of the Iron and Steel Industry (London, 1967) Charles Cammell in 1845 paid only 2½d. per yard for his site.

3 The bulk of this information is taken from A. C. Marshall and H. Newbould, The History of Firth's (Sheffield, 1924), pp.1-11.

a group of six crucible melting holes in Charlotte Street and gradually building up a reputation for excellence in cutlery and tool steels. By the end of 1846 they were employing thirty men; by 1851 the need for expansion brought about a move from their original site, of about a third of an acre, to a green field location on Savile Street, of some forty acres, eventually to become the Norfolk Works. At that time :[1]

> '.... as Savile Street was only post and rails and edge stones, it was heavy work bringing large stones down the road .... The ground was clayey and in wet weather very soft. The wheels sank deep and it became quite an interesting sight watching the men extricating them. All the way down from the Twelve O' Clock Inn the land was taken for brickmaking and while building was going on on one side of the road, clay was being tempered and bricks made and burnt on the other'.

The crucible furnaces were at work by the end of 1851 and a dinner was given at Christmas to all the workmen, in the empty building which was to house the rolling mill, and the reheating furnaces were lit to warm the guests.

Steelmaking activities from the death of Huntsman, in 1776, to the establishment of the large East End steelworks is not well documented. The directories for the period vary widely in their completeness; a few appear to be precise in their division of steelmakers into

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1 Marshall and Newbould, loc.cit., p.10.

refiners, as compared with converters, but it is not unusual to find the information to be in conflict with the facts available elsewhere. Taking the evidence at its face value, however, the number of firms involved in any kind of steel-making in the Sheffield area rose from 18 in 1797 to around fifty by the early 1820s, then to something of the order of eighty by 1835 and to 110 by the early 1850s. It is of interest to compare the evidence given by the 1839 Directory,[1] which appears to be fairly precise in its categorisation of steelmakers as refiners and converters, with that arrived at by Le Play, as a result of his study of steelmaking in the area from 1836 to 1842.[2] Le Play indicates a total of 33 converters and 51 refiners, some of whom obviously carried out both operations. The 1839 Directory entries may be divided as follows :

Converters	9
Refiners	19
Converters and Refiners	21
Manufacturers	29

Ignoring the group classed as manufacturers, the total engaged in converting and those in refining agrees reasonably closely with Le Play's data. Unfortunately, there are manufacturers listed who are known to have

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1 W. and C. Robson, Birmingham and Sheffield Directory, (London, 1839).

2 Le Play, loc.cit., p.639, p.693.

been converters and/or refiners, as in the case of Wm. Jessop at Park Works, quite definitely engaged in both operations, as were J. Greaves and Son, whilst Pickslay and Company were certainly engaged in crucible steel melting. This particular example shows the uncertainties of attempting to determine a detailed picture.[1] Le Play, however, states that the 51 melting shops covered by his findings had between them 774 melting holes, which indicates that a shop with between ten and twenty holes could be considered as normal. Around 1837, however, it has been shown[2] that Sandersons had 83 melting holes - 53 of them taking two crucibles each[3] - Greaves and Sons and Naylor and Company had at least thirty each, Wm. Jessop had 26, William Ibbotson Horn had 20 and Ibbotsons, at Globe Works, probably had 22 melting holes. Within ten years, however, the number of melting holes had almost doubled, a figure of 1494 melting holes being given for 1853.[4] By this time, the Millsands Works of Naylor, Vickers and Company contained 90 melting holes; both Jessops and Sandersons had found it necessary to enlarge their operations by taking additional premises on

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1 J. G. Timmins, The Commercial Development of the Sheffield Crucible Steel Industry, Unpublished Thesis (Sheffield, 1976), pp.52-66 discusses the problems in considerable detail.

2 Timmins, loc.cit., pp.56-57.

3 An interesting description of operations at the West Street Works of Sandersons in 1845 can be found in Appendix WW.

4 C. F. Waern, 'Om Jerntillverkningen och Jernhandeln', Riksdag Bilaga (1853-54), pp.49-50.

the outskirts. Jessops had commenced operations at Brightside and between their two works were employing about 120 melting holes and probably were, by then, the largest steel producers in the area; Sandersons had commenced operations at their second site at Darnall. Meanwhile, some of the works within the town were expanding; in 1854, the two adjoining works of Bedfords and Butchers, on Penistone Road, installed 24 and 68 cast steel furnaces respectively, whilst modest additions were made at this period in some of the smaller central town works.[1]

It becomes clear that Sheffield steelmaking activities were evolving along two distinct lines. On the one hand, there were the smaller establishments, generally with a background tradition in the cutlery and edge tool trades, within the old town; on the other hand, outside the old built up area, as it had been before the coming of the railway - in the 'East End' as it came to be known - were the beginnings of the large scale steelmaking and engineering concerns. Between them, at the middle of the century, they were producing about 90% of the national steel output and, moreover, almost half the total world output.

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1 Timmins, loc.cit., p.60.

II Sheffield in Transition: 1850-1890

The next thirty or forty years was a period of major change in steelmaking activities. Up to 1850, any thought of making steel in this country, other than by the cementation and crucible processes, could have been discounted. Likewise, any crucible steel not produced from cemented Swedish bar iron would have been regarded as inferior. Moreover, the crucible furnace, as developed by Huntsman, was the only conceivable means of producing good steel. Then, in quick succession, came a series of events the implications of which could not be ignored. First came the idea that serviceable steel could be obtained from the puddling furnace; then Swedish cast iron became available in this country; this was quickly followed by Bessemer's revelations at Cheltenham in 1856; then came the work of Siemens, who not only provided a rival process to Bessemer but offered an alternative furnace to the crucible steelmaker; finally, Gilchrist Thomas demonstrated to the world how to make good steel from phosphoric iron ores.

The technological impact of these changes and the implications of the rise in alloy steel production have already been noted, but the effect which they had on the Sheffield steel trade requires clarification here. For the first few years, indeed, they had little effect;

there was a steady demand for steel as it had been produced for the previous half century. The release of Swedish cast iron, however, obviously set a number of the Sheffield steelmakers thinking. They reacted in different ways. Edward Vickers had long been investigating the economies of the crucible process and it was he who pioneered the use of mixed charges of cast iron and wrought iron in the crucible, rather than incur the expense and delay of cementation. The release of a first quality cast iron, low in sulphur and phosphorus, met his needs ideally. The logical conclusion from this kind of thinking was the erection of the new River Don Works, to which Vickers moved a few years later; here the largest concentration of crucible melting facilities ever to be built in Sheffield did not have a single cementation furnace on the site.[1] Others, including John Brown, Charles Cammell and Thomas Firth, installed puddling furnaces. Brown and Cammell made wrought iron plates, but both also produced puddled steel in Sheffield. Brown, indeed, was most probably selling some of it as 'JB Melting Base' to his fellow crucible steelmakers in Sheffield by 1862. Thomas Firth kept his puddling operations apart, at Whittington, and it was there that his 'famous puddled steel' was made;[2] his Sheffield activities remained

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1 As has been pointed out earlier, however, he eventually moved to the use of charcoal, rather than cast iron, as his carburising addition to the bar iron.

2 A. C. Marshall and H. Newbould, <u>The History of Firth's</u> (Sheffield, 1924), p.24.

firmly tied to the crucible process for a further twenty years or so.

A picture of the situation in Sheffield around 1859-1860 is available from a French source. Discussing the estimated production of 50,000 to 60,000 tons per annum in the Sheffield area at this time, the following breakdown is given :[1]

Puddled steel and common spring steel	50%
Common cast steel, better than the previous	15%
Cast steel for mill spindles, spades, shovels, etc.	10%
Cast steel of better quality, welded for various types of tools and cutlery	10%
Cast steel of good quality for the above	10%
Cast steel of first quality for drills, engraving tools, etc.	4%
Cast steel of extra quality for very superior tools	1%

The same report makes it quite clear that the age of the large manufacturer had arrived, pointing out that the major half dozen works were each capable of producing up to 5,000 tons of steel per annum, accounting between them, at this date, for more than the total production of the area some twenty years earlier; at the same time, the point is made that they also produced about as much

1 L. E. Gruner and C. Lan, L'État Presént de la Metallurgie du Fer en Angleterre (Paris, 1862), pp.788-789.

as the remaining eighty or so smaller firms in the region.[1] Costs and selling prices are also quoted :[2]

	Cost per ton	Selling Price
Spring bars, puddled from English pig	£ 8.17.6.	£10. 0.0.
Spring bars, puddled from Russian pig	£11. 2.6.	£12.10.0.
Spring bars, puddled from Swedish pig	£12. 7.6.	£14.10.0.
Spring bars, from cemented English iron	£13.18.0.	£14.10.0.
Spring bars, cast steel from common Swedish iron	£24.10.0.	£25.10.0.
Bars in superior quality cast steel from best Swedish iron	£49.10.0.	£52. 0.0.

These figures relate to spring bars. For forged bars, three inches in diameter and five feet long, for piston rods, the price was £60 per ton in 'refined cast steel' and similar prices applied to small section bars for cutlery. Crinoline ribbons - 2½ inches wide by 20 gauge (about one twenty-fifth of an inch thick) - were produced from English iron, cemented and then melted and sold at £32 per ton, giving about £3 per ton profit; a similar product but made from Swedish iron sold at £40 per ton, with a similar profit margin. One wonders whether the better quality material

1 Gruner and Lan, loc.cit., p.791.

2 Ibid, pp.803-805.

was less liable to failure in service! Also made from cast steel, derived from the common Swedish iron, were spade plates (10 inches wide by 12 or 14 gauge), selling at £28 per ton, and saw strip (6 feet long, 8 inches wide, by 9 gauge) at £33 per ton. Thin strip for metal pens (26 or 27 gauge) cost £45 per ton, whilst five foot diameter blanks for circular saws could be sold for £80 per ton. Rails were made in puddled steel (£17 per ton) or cast steel (£24 per ton), whilst boiler plate from cast steel, up to 24 square feet in area and one quarter inch thick, could be had for £45 per ton. It seems that a profit of around 10% on manufacturing cost was usual, except for the small quantity of 'superior quality' cast steel, where up to 20% could be expected.

There were indications at this period, however, that Sheffield would retain its position as the main steelmaking centre and would enter the bulk steelmaking production field. Both Brown and Cammell retained their cementation and crucible furnaces, and indeed increased their capacity, as can be seen quite clearly from the surviving drawings of the works from this period. Both of them, however, made major changes when Bessemer had perfected his process at his Sheffield works.[1] John Brown took out a licence from Bessemer in

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1 This was in 1859; for further details, please refer to Chapter 9. (See pp.405-408).

1860; Cammell followed suit in 1861. Between them they used Bessemer steel to found a new type of industry in South Yorkshire, meeting the demand for materials from the railways; for axles, springs, buffers and, above all, for rails.[1] By 1865, John Brown was making almost half the British output of rails and this represented at least three quarters of his total production. Meanwhile, Cammell had found his capacity at the Cyclops Works insufficient to meet the demand and had taken over the Bessemer plant set up a few years previously, by Adamson, at Penistone. At the end of 1863 this works was in full operation on railway materials. Even this was not sufficient. In 1872 he found it necessary to build a large new works at Dronfield, alongside the newly opened main line to Sheffield; the rail making operations from the Cyclops Works were transferred here and greatly expanded. Meanwhile, John Brown, who always seems to have endeavoured to be as self sufficient as possible, purchased a haematite iron ore mine in Spain, installing a blast furnace on Carlisle Street to produce his own raw material to feed his Bessemer converters. Tradition has it that he also built a smaller blast furnace to smelt the ferro-manganese he needed. In 1872, two further Bessemer steelmakers appeared on the Sheffield

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1 K. Warren, 'The Sheffield Rail Trade, 1861-1930: An Episode in the Locational History of the British Steel Industry', Trans.Inst.British Geography (1964), pp. 131-155 covers this particular development in depth.

scene: The Phoenix Bessemer Company at the Ickles, near Rotherham, and Brown, Bayley and Dixon at Attercliffe. By 1873, the Sheffield area was producing about a quarter of a million tons of steel rails, one third of the British output.

Once again, Sheffield was doing very profitable business in a situation which was, to a large extent, illogical. It was entirely dependent on Furness and Cumberland for its major raw material - apart from the product of the John Brown furnace - since the pig iron required by the Bessemer process had to be a low phosphorus material. It did, however, have some advantages, with local coal and refractories. Moreover, it was entering a new branch of the trade and therefore installed specifically designed equipment, which placed it in a better position than the old wrought iron rail producers, who were now making steel rails with antiquated and mainly unsuitable plant. Its greatest advantage, perhaps, was that Sheffield was synonymous with quality, as far as steel was concerned, despite the enormous difference between the new Bessemer steel and the celebrated old crucible steel. The Welsh ironmakers, on the other hand, had gained themselves a very poor reputation for their wrought iron rails and had to live this down, whilst Barrow, the largest individual works making steel rails, had to build up its reputation from scratch. With demand high and prices good, the transport costs of the raw materials into Sheffield and the rails out from Sheffield could well be absorbed.

Then the tide turned. Exports fell from the middle of 1873, particularly to America, and within two years John Brown had withdrawn from the rail trade, moving over to general engineering materials. By this time, the Phoenix Works had failed and Brown, Bayley and Dixon were making losses, though Cammell, both at Penistone and Dronfield, continued to be reasonably busy. Elsewhere, the blast furnace based plants began taking the liquid metal direct to the Bessemer converter, instead of casting it into pig and remelting it, when required, in a cupola; the savings achieved in this way allowed plants like Barrow, Ebbw Vale and Dowlais to remain competitive in world markets. Despite improvements in trade, in 1877-78 and 1881-82, Cammell found that transport costs were too much of a burden and he took the surprising decision to move the entire Dronfield plant to Workington, alongside the blast furnaces of the Derwent Iron Company, where liquid iron could be used and the finished rails could be transferred for shipping abroad, at minimum cost. There was only a six month hiatus in production involved in this move; considering the implications, the planning must have been exceptionally good. It is important to note that the Penistone works continued to make rails for the home market until about 1920, but by 1885, the Sheffield area share of the British rail market was down to about 5%.

Vickers remained true to the crucible process. The production of steel castings, which was pioneered in the Millsands Works from about 1855,[1] was greatly enlarged on the transfer of activities to the River Don Works. The melting capacity there, however, needed other outlets. One of these, following logically from the making of large steel castings, was the production of large ingots[2] to be forged subsequently into gun barrels or engineering components. Another speciality was the production of railway tyres.[3] Cylindrical ingots were parted into cheeses, which were then flattened, punched and rolled on a mill specially designed by Vickers and his chief engineer, Reynolds. On the other hand, the older

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1 This operation was carried out by the method invented by Jacob Meyer of Bochum; in Sheffield the use of ganister mixed with a certain proportion of fired clay was found to be eminently satisfactory as a moulding material. Apart from bells, for which Vickers became noted, they produced cast wheels, complete with spokes, gearwheels, pistons and all types of railway crossings; S. Jordan, L'Industrie du Fer en 1867, Vol.4 (Paris, 1871), pp.462-463.

2 S. Pollard, A History of Labour in Sheffield (Liverpool, 1959) reports the production of a 25 ton ingot in 1869 using 672 crucibles; the original reference has not been found. A report of 1867 indicates the feasibility of making a single casting of the same weight from 576 crucibles: Engineering, 25th October 1867, p.384.

3 Engineering, loc.cit., p.384.

traditions were not forgotten; tool steel bars, both with the 'Marshall' and 'Vickers' trade marks, were produced in fair quantity.[1] Two products from this period are still preserved in the offices of Naylor, Vickers and Company, now the headquarters of the River Don Works of the British Steel Corporation; one is a twenty pounder rifled gun made from a block of crucible steel supplied to the Royal Gun Factory in July 1862 (Figure 32), and the other is a steel bell cast in 1873, some 32 inches in diameter at the base and 30 inches high (Figure 33).

Firths, although they carried out puddling operations at Whittington, concentrated on crucible steel melting at their Norfolk Works in Sheffield.[2] They too produced bars for tools and cutlery, but they had commenced to make gun forgings as early as 1852 and, by 1864, had 360 melting holes and two 25-ton steam hammers. They were also producing armour piercing shells. It will be remembered that in 1874 they made a twenty ton ingot for a gun tube forging;[3] Figure 27 has already been included

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1 Jordan, loc.cit., p.300. The continued use of the 'Marshall' mark some forty years after Jonathon Marshall went out of business and his works at Millsands were taken over by Naylor, is a tribute to its continuing tradition of excellence.

2 Firth Brown, 100 Years in Steel (Sheffield, 1937) provides a resumé of the history of both Firths and Browns.

3 Sheffield and Rotherham Independent, 28th April 1874. The article is reproduced in full as Appendix OO. It should be noted that there is a discrepancy in weight between the contents of the crucibles (which do indeed amount to just under 20 tons) and the weight of a 13 foot length of 42 inch diameter ingot, which would have weighed almost 28 tons.

to show a similar operation witnessed by the Prince and Princess of Wales, on their visit to the Norfolk Works the following year.[1]

As time went on, however, the inconveniences of the small scale crucibles for such large scale activities made the introduction of alternative means of providing bulk steel a necessity if such operations were to be part of the normal production pattern. In 1879, John Brown installed Open Hearth furnaces, to be followed in 1884 by Firths and, before 1890, by both Vickers and Jessops. The age of the Sheffield forgemaster, with his hydraulic presses,[2] specialised heat treatment furnaces and vast machine shops, to service the engineer and the shipbuilder, as well as to furnish the arsenals of the major powers, had arrived.

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1 Col. Maitland, 'On the Metallurgy and Manufacture of Modern British Ordnance', J.I.S.I. (1881, Vol.II), p.429, reported that Firth's gun tubes, made entirely from crucible steel, were of high excellence and were, without doubt, the most trustworthy. Those from Vickers came out well but were not quite as reliable, being made from Siemens Martin steel. It must be pointed out, however, that T. E. Vickers, in the discussion (p.501) made it quite clear that the author was in error; their forgings were also from crucible steel but it was produced from the gas fired Siemens furnace, and not by the Siemens Martin Open Hearth process.

2 Hydraulic presses were not new to Sheffield. Both Cammells and Browns had installed them as early as 1863, (Firth Brown, loc.cit., p.8; A. Allison, 'One of the East End Works: The History of Cammell and Co.', Sheffield Trades Historical Society News Review, March 1952). What was new was their size and their proliferation during the last twenty years of the nineteenth century. Firths installed a 3000 ton press of their own design in 1888; John Brown and Co. had installed a 'large press' in 1879 and by 1900 had no fewer than ten presses in operation, the largest being 8000 tons capacity (Firth Brown, Souvenir of a Visit to the Atlas and Norfolk Works, 1954).

Firths by combining the contents of a 45-ton, two 25-ton and one 10-ton furnace, were able to cast ingots of 100 tons in weight during the 1890s and :[1]

> '.... the crucible process, which had served Firths so well for over forty years, was abandoned in 1884 for the production of ingots for forgings, though retained for the fine quality tool steels for which, indeed, it was essential'.

This, indeed, was the general picture in the larger Sheffield steelworks.

Meanwhile, firms like Sandersons were also expanding; they added 132 melting holes to their Darnall Works in 1872. Andrews' Toledo Works, with 144 melting holes, was commissioned in the same year.[2] Samuel Osborn, who had started operations in 1852, added considerable extra capacity in 1885,[3] with the erection of a 24-hole gas fired furnace. Seebohm and Dieckstahl commenced with 18 melting holes, in 1865, within three years moved to new premises with 48 melting holes, and were soon to become famous as one of the major tool steel makers in the town. It is interesting to note that their new crucible shop, like that of Huntsman and Company but unlike most others, showed parallel rows of transverse chimney stacks, six in number

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1 Firth Brown, 100 Years in Steel (Sheffield, 1937).

2 Timmins, loc.cit., pp.187-188.

3 Ibid, p.195.

in this case, each covering a row of eight furnace holes.[1] At the same time, many of the old small town establishments continued in operation, all making cutlery and tool steel. Times were not always propitious; the period from 1873 to 1896 was indeed referred to in retrospect as 'The Great Depression', but even in these years :[2]

> 'In Sheffield, it was held that twelve crucible holes would run a carriage and pair, then the top status symbol'.

III Sheffield After 1890: Special Steel from Crucibles

By 1890 it needed but casual observation to decide that there were, indeed, two distinct trades in the Sheffield steelworks. The larger, more elaborate part of the trade, producing ordnance and engineering forgings, does not really come within the terms of reference of this study, but a survey of the South Yorkshire scene in 1900 gives an indication of the way the old established firms had moved. The traditional methods receive no mention,

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1 According to the firm's letterhead, a copy of which was found inside the back cover of the copy of H. Seebohm, On the Manufacture of Cast Steel (Sheffield, 1869), which was consulted some years ago.

2 Arthur Balfour and Company, 1865-1965, a privately published history (Sheffield, 1965), p.22.

but the furnace population otherwise is quoted as follows :[1]

	Blast Furnaces	Bessemer Converters Acid	Bessemer Converters Basic	Open Hearth Furnaces Acid	Open Hearth Furnaces Basic
Brown Bayley and Co.	-	2	-	4	-
Bessemer and Co.	-	2	-	2	-
Samuel Fox and Co.	-	2	-	-	-
Steel Peech & Tozer	-	2	-	-	-
Cammell - Sheffield	-	-	-	6	-
Cammell - Penistone	-	4	-	-	-
Parkgate Iron Co.	5	-	-	1	5
John Brown & Co.	3	-	-	5	-
Thos. Firth & Sons	-	-	-	4	-
Vickers, Son & Maxim	-	-	-	4	-
Hadfields Foundry	-	-	-	3	-
Others	-	-	-	7	-

Unfortunately, the author gives no indication of furnace sizes. The preponderance of acid furnaces over basic and the preference for Open Hearth steel, however, is clearly indicated.

Those larger works which had originally been based on the crucible process but had now graduated to operations on a much vaster scale, however, all found it prudent to retain some small proportion of their crucible melting capacity, together

1 H. H. Campbell, The Manufacture and Properties of Steel (New York, 1907), pp.520-521. The same source quotes South Yorkshire as producing some 550,000 tons of steel in 1900, this being 12% of the British total. Parkgate Iron Company was at that time the only producer of pig iron in the area in the accepted sense. John Brown's furnaces were part of the self sufficiency programme mentioned above; what is intriguing here is to note that there were supposedly three blast furnaces in the John Brown works. Surviving photographs show only two; the third is something of a mystery.

with a few small hammers, to produce their own tool steel and special requirements. Most of their crucible furnaces were eventually demolished and the sites reused - land was at a premium in the now overcrowded East End, a very different situation from that of the 1840s. The cementation furnaces also went out of use and were taken down; John Brown had eighteen in the 1860s but not one can be seen on the 1901 drawing of the works.

The smaller works, nevertheless, on the whole continued to thrive. The new innovations discussed earlier were duly considered, but were only brought into operation as thought reasonable in this very conservative trade.[1] They would still use blister steel for all important melts, converting their own iron or having it hire-converted for them, or even buying it in. Many charges, however, would be of bar iron, with suitable additions of Swedish white iron, with the inevitable spiegeleisen as 'sweetener'. Charge material could, indeed, be bought in from suppliers such as Doncasters, one of whose sales leaflets is reproduced in Figure 34. The weight charged to the crucibles would have increased; 50 lb. to 60 lb. was not unusual, whilst some firms had gone up to 70 lb. Whilst crucibles were still

1 Some comments relevant to the period prior to 1914, given me by an old hand at the trade many years ago, may be found in Appendix XX. The author was J. O. Vessey, Esq., who ran one of the smaller steelworks in the town.

generally made from bought-in clay, on the premises, the extended use of plumbago crucibles for special melts was becoming rather more common, particularly for some of the alloy steels, the scrap from which would be carefully segregated, so that the precious alloy elements could be recovered by inclusion in the next melt of such materials. The replacement of coke fired furnaces by gas fired ones, however, was very much a matter of individual choice; few small establishments would have the need, whilst the medium sized ones had their prejudices. Both Seebohm and Dieckstahl and Huntsman and Company thought fit to move from their established premises to sites on the outskirts of Attercliffe, during the last few years of the nineteenth century, and both installed only new banks of coke fired crucible holes. Firths, on the other hand, wishing to concentrate their tool steel production on a separate site so that it could be run on its own lines detached from the larger production at the Norfolk Works, built what could be classed as a medium sized works at Tinsley, with the most modern design of gas fired furnaces, together with hammers, rolling mills and heat treatment facilities; this was in 1907.

As time went on, more and more accent was placed on alloy tool steel production. As it so happens, production records from Seebohm and Dieckstahl (later to become Arthur Balfour and Company) have survived for the period

1883 to 1922 and these are summarised in Table VI.[1] From this, it will be noticed that the peak production comes in 1899, the first year of operation of their new melting shop at Greenland Road. It is also clear that there are very few individual years subsequently when this capacity is fully occupied. This would tend to indicate that the demand was not up to expectations. One point which should be noted is the call for high speed steel during the war years. The available information also makes possible a differentiation between the various grades of carbon steel produced and the figures for a few selected years have been extracted and summarised in Table VII. These figures indicate a trend to the replacement of some of the high carbon materials by alloy steel in the early years of the century, but a return to the higher carbon variants during the war despite the growing production of high speed steel. Such a situation is not incompatible with the consideration that alloy steels were preferable to the special carbon steels but that, under wartime conditions, the demands for high speed steel could not be fully met and that the shortfall was met the best way possible by producing the best carbon steels again.

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1 These figures come from production records and memorandum books deposited with the Sheffield City Archives, Ref. BDR 76 and BDR 97-1/5. This organisation could be considered as typical of the medium sized Sheffield steelmaking enterprises; it is, of course, unwise to make any generalisations based on one single example.

In this context, the comments of an American observer on the Sheffield steelmaking scene after the war are relevant.[1] He points out that there were about 150 makers of high speed steel in Sheffield in 1920, twenty of whom could be considered as reasonably large producers, most of them also producing other classes of crucible steel and none of them exclusively making high speed steel. He also makes it clear that the majority sent out their ingots for hire forging and rolling, as this was still the standard practice in the district. The fall in demand had, however, ensured that most producers were working to only 50%, or less, of their capabilities. The comments on the use of iron are interesting as showing the strength of conservatism in the Sheffield trade :

> 'Swedish iron is the base for all British high speed steels. This is normally delivered at the works in ⅝" x 3" bars which are broken up and cemented. A little selected scrap is also used .... A certain amount of commercial tool steel was made during the war from British iron and steel, low in sulphur and phosphorus, but it is now asserted that Swedish iron is exclusively used in the manufacture of high speed steel in Sheffield, although it costs about 10d. per pound'.*

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1 P. M. Tyler, 'High Speed Steel Manufacture in Sheffield', The Iron Age, 10th February 1921, pp.371-374.

* This is equivalent to £93 per ton, a much higher figure than appears in the Doncaster records for the time. The highest price quoted was £80 in 1918; thereafter it fell to £53 per ton in 1919 and was down to £30 per ton in 1922.

He goes on to consider the crucibles :

> 'As compared with American crucible practice the outstanding feature that will be noted in Sheffield practice is the small charge weight employed. The individual pots hold from 40 lb. to 70 lb. of metal, the average charge being about 60 lb. Graphite crucibles are rarely used in Sheffield, the pots being made almost exclusively from local clay. The pots are frequently made in a small shed attached to the steelworks. Extreme care is given to the manufacture and inspection. A few mechanical pugging mills are now in operation but many of the steelworks still employ the ancient practice of kneading the clay in small batches by treading. The workmen mix up the clay with their bare feet, as it is claimed by this method that any foreign matter or coarse fragments can be more positively detected. The pots are about 18" high and 9" in diameter and weigh about 30 lb. each. After firing, they are carefully inspected and only the best ones are chosen for high speed steel'.

The observer also comments that most of the plants used coke as fuel, although there were several works in which gas firing was employed; he noted that gas firing was not popular, owing to the greater risk of rupture of the crucibles. He described the casting of the ingots, pointing out that the metal was frequently teemed direct from crucibles to moulds, although mixing in a ladle was said to be becoming more common. A full description of the use of a dozzle, and its implications on metal economy, seems to indicate that such an item was not in general use in America; if so, this is rather intriguing, some sixty years after its introduction in this country by Mushet, and its subsequent general use in all the Sheffield steelworks.

Within a few years of this report, there came the introduction of a new type of crucible furnace - for this is how the high frequency furnace should be considered. It had a refractory container, cylindrical in form, around which was provided a water cooled copper coil. The connection of this coil into the circuit of a high frequency generator produced eddy currents in the space within the crucible. With a charge of metal, such as that normally used in the crucible process, within the field of the coil, heating occurred, leading to the eventual melting of the charge. The box containing the furnace could then be tilted about its front edge and the molten metal poured out over the lip into a waiting ingot mould - or, more usually, into a ladle, from which the metal could be run into moulds. Originally, such furnaces were operated simply as mechanised crucible furnaces, using a protective slag cover made by adding a sufficient quantity of broken bottle glass, completely inert and without any deleterious effect on the crucible itself. The first furnace to be applied to the commercial production of steel was at the Imperial Steel Works of Edgar Allen and Company in Sheffield, starting its production run on 6th December 1927. A report on its use[1] was careful to point out that the function of the crucible process had been to

1 'Progress in the Production of Crucible Steels', Edgar Allen News, December 1928, pp.278-279.

melt materials to the required analysis and to separate out all the slaggy matter, but that no other purification had proved possible. It also indicated that the fuel in the normal crucible process, be it coke or producer gas, was always rich in sulphur, some small proportion of which would always enter the steel, since the crucibles were not impervious to gases. With the induction furnace, however, the melting of high purity materials could be achieved in a neutral atmosphere, with no fear of external contamination - a very real advance in practice. The report also gives details of a run of 72 consecutive heats in the furnace, from 31st May to 12th June 1928, covering 55 melts of high speed steel, 8 of alloy steel and 9 of carbon steel :

Average weight of charge	5 cwt.
Total weight of topped ingots	343 cwt.
Total power consumed	13881 units
Average power per heat	193 units
Power per ton of steel charged	770 units
Power per ton of topped ingots	810 units
Number of pots used	6
Average life of pot	12 heats
Average weight of steel produced per pot	57 cwt.

It is of interest to note that the refractory lining is still referred to as a 'pot' - it seems to have been a pre-fired interchangeable container in the early days. The same report gives details of comparative tests on the cutting capabilities of high speed turning tools of similar compositions made from the new furnace and from a gas fired crucible furnace; in all cases the high frequency melted material gave the longer life.

This furnace had a lot to recommend it; it was clean, it could be switched on or off at will, it did not require preheating, the crucible was semi-permanent and the teeming did not depend on the manual dexterity of a highly specialised craftsman. It would produce more metal than could be manually handled in a single crucible and the argument on lack of contamination by the fuel was a genuine one, since sulphur had always been one of the undesirable impurities in steel. It also came at a time when there was a general decline in trade, culminating in the depression of the early 1930s. During this period many steelworks closed down most, if not all, of their crucible holes. Some of them were opened up again when better times returned but, in many cases, they were replaced by one or two high frequency furnaces of a somewhat larger size than the Edgar Allen prototype, up to a ton or so in capacity. At the same time, the use of a pre-formed crucible within the coil gave way to the ramming of a powdered lining material between the coil and a metal former. There also was now the possibility of putting in a more reactive lining in this way, one of a basic character. By 1938, Firth Brown had a six-ton furnace, with a dolomite lining, used to produce stainless steel as well as tool steel, capable of purifying the metal charge in that both the sulphur and phosphorus contents could be reduced by suitable adjustment of the melting procedure. This was indeed a far cry from the crucible holes which had occupied the site only a few years before. At the same time, there were also, in the same melting bay, high frequency furnaces of only ten hundredweight capacity, with acid linings, melting tool steel and using procedures which derived directly from the old crucible steel practice.

Coke fired crucible furnaces were still to produce steel in some of the smaller works for at least a further twenty years, but the larger concerns turned over quickly to the high frequency furnace and, indeed, to the larger production capabilities of the electric arc furnace, which had been making steady progress since just before the First World War. Then came the Second World War - and with it an urgent demand for more tool and high speed steel. The effectiveness of the crucible process in producing small ingots in these difficult-to-forge materials had not been forgotten, nor had the crucible men forgotten their skills. Crucible holes in some works had merely been covered up with floor plates and those which could be were opened up again, as at Firth Brown. Elsewhere, as at the Abbeydale Hamlet, the shops had merely been abandoned. Abbeydale in fact, had been closed down in 1931 and was already being restored as a proposed industrial museum site, by the Society for the Preservation of Old Sheffield Tools,[1] when the war broke out. It was taken over by Wardlows and produced something between 400 and 500 tons of the badly needed high speed steel before being abandoned again.[2] It was in this manner that Huntsman's contribution to steelmaking sounded its swansong - in a manner indeed which would have appealed to his strong patriotic sentiments.[3]

Some crucible furnaces lingered on in Sheffield, in some cases doing rather curious tasks, such as making cast stainless steel road studs, by melting down stainless turnings with a small amount of cast iron to give the necessary fluidity to the metal, or even melting down scrap silver! As far as is known, the last crucible furnace in Sheffield closed down as late as 1968; this one was still making tool steel until it had to be demolished to make way for road improvements in the area.

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1 Later to become the Sheffield Trades Historical Society. The sum of £1250 had been collected and work on the restoration of the site was halted by the outbreak of hostilities. The eventual restoration of the site in the 1960s cost at least sixty times this figure!

2 R. M. Ledbetter, Sheffield's Industrial History from about 1700 with Special Reference to the Abbeydale Works (1971), M.A. Thesis, Sheffield, pp.212-213.

3 It appears that the same thing happened in the United States; the production statistics show that there was a noticeable, if small rise in crucible steel production during the war years, before final extinction.

IV Crucible Melting Elsewhere in Britain

The surviving evidence points to little crucible melting activity outside the South Yorkshire area.

In the North East, the crucible process was introduced at the Swalwell establishment of Crowley, Millington and Company in 1810.[1] John Spencer built both cementation furnaces and crucible melting holes at the Newburn Works, near Newcastle, some time between 1830 and 1845, and extended his facilities in 1853. By 1863, this was the largest steelworks in the North East, having 36 melting holes.[2] By this time, six crucible melting holes had been established at Derwentcote and there were a further six at the Dunston Works of Messrs. Fullthorpe and Company.

In Liverpool, the Mersey Steel Company[3] was supplying cast steel under its own trademark in 1834; nothing is known of the facilities available, but

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1 T. Spencer, 'On the Manufacture of Steel in the Northern District', British Association Handbook, Newcastle Meeting (London, 1863), p.766.

2 Ibid, p.768.

3 This was presumably the Mersey Steel and Ironworks of which William Clay was later the Manager. He was involved with steel puddling in the 1850s and with the production of steel rails in quantity by the Bessemer process between 1865 and 1880. The works closed in 1899. Their involvement with the crucible process is not documented elsewhere.

testimonials to the high quality of 'Roscoe, with a Crown' brand, from users in the North West, North Wales and Birmingham, have been found in a bundle of papers in an engineering shop in Cornwall.[1] There is a further reference to a Liverpool firm of crucible steelmakers. J. C. Fischer visited the 'Steel and Iron Works' of Horsefall and Company on 29th October 1846[2] and found the melting shop to be a small one, with only eight crucible holes; moreover, these only accommodated a single crucible each instead of the more usual two. The crucibles were of the standard shape, but thicker, and their fracture was almost white since they were made from pure Stourbridge clay without any coke or graphite addition.

In the Midlands, the Brades Works had either twelve double crucible holes or twice that number single holes in 1870; the inventory of 1868 and the lease of 1870 do not agree in this respect, but quite clearly they were producing crucible steel.[3] Elsewhere in the Midlands, there was some

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1 T. R. Harris, 'Further Extracts from Old Letters and Circulars', Edgar Allen News, Vol.32, No.376 (October 1953), p.235.

2 J. C. Fischer, Tagebucher (Zurich, 1951), pp.593-602.

3 Lee Crowder Papers, Birmingham City Libraries. No. 930 is an Inventory of the Brades Works in 1868 and refers to a casting house, 58 feet by 33 feet 6 inches with 24 Cast Steel Pot furnaces with pot rooms and annealing stoves. No.931 is a Lease which describes a 'Large Steel Casting House', 56 feet by 31 feet 6 inches, a lofty brick building with chimneys at each end with 12 pots.

crucible steel melting at Isaac Jenks' Minerva Works in Wolverhampton[1] and by the Darlaston Steel and Iron Company at Darlaston.[2] Mushet had crucible melting facilities at the Titanic Steel Works in the Forest of Dean in the 1860s; the scale of operations suggests that five or six double holes were involved.[3] There is also a brief reference to a William Walker of the Eagle Steel Works in Bristol offering octagon steel for taps and turning tools in 1839; this was presumably crucible steel, but there is no evidence that he made it himself.[4] There is also a reference to the melting of steel by Mr. Webster of Penns, near Wolverhampton, between 1827 and 1844[5] but this was almost certainly carried out at his Killamarsh works.

There is one brief mention of operations in London, in that Fischer took some steel for forging to the London Steel Works in October 1827. This establishment was stated to be on the left bank of the Thames, near to Vauxhall Bridge and belonged to Messrs. Thompson and

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1 S. Griffiths, Guide to the Iron Trade of Great Britain for 1873 (ed. Gale) (Newton Abbot, 1967), p.70 and Advertisement.

2 Ibid, p.72, p.161 and Advertisement.

3 Sheffield City Libraries, Ref. MD 1193-4.

4 T. R. Harris, 'Some Old Letters and Circulars', Edgar Allen News, vol.30, No.359 (May 1952), p.138.

5 J. Percy, Metallurgy: Iron and Steel (London, 1864), pp.841-842.

Johnson, cast steel makers and iron refiners.[1]

The records of the international exhibitions tend to confirm the lack of crucible steelmaking on any important scale, other than in the Sheffield area. There is, however, one exception: Hawksworth and Company of the Avon Works in Linlithgow exhibited engraving plates and gun barrels in crucible steel at the Paris Exhibition in 1862.[2] William Hawksworth, the manager of these works, made various contributions to the discussions at Society of Arts meetings and seems to have been well versed in crucible steel melting procedures.[3] He took over the Linlithgow operations in 1855, leaving in 1865 to manage the Gartness Iron and Steel Works, near Airdrie. He was succeeded at the Avon Works by Stones and Robertson, who made steel castings there until 1871. The works were then used for the production of shovels and tinplate, until Charles W. Robinson and Company resumed steelmaking there, from 1878 to about 1890. During this period metal shears, with blades up to

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1 Fischer, loc.cit., p.455.

2 S. Jordan, L'Industrie du Fer en 1867, vol.4 (Paris, 1871), p.304.

3 The background to William Hawksworth is not known. There was a Hawksworth involved in steelmaking in Sheffield at this time, Wilson, Hawksworth and Moss being steel refiners and converters according to W. White, History and General Directory of the Borough of Sheffield (Sheffield, 1833). The firm later became Hawksworth, Ellison and Moss, and T. B. Hawksworth was a partner at the time that Charles Kayser came to the firm from Germany in 1860. The later name was Kayser, Ellison and Company. No relationship with William Hawksworth has been traced, however.

fifteen feet in length, as well as steel castings, were produced. The works were then abandoned. There is no record as to the extent of crucible steelmaking activity at the Avon Works; at Gartness, however, it is known there were twelve crucible melting holes.[1]

As far as other steelmaking activities in Scotland are concerned, a report given in 1885 stated :[2]

> '.... there are now, or were very lately, six firms producing crucible steel and that all in all there is a power of production of something like 1500 to 1600 tons of such steel annually. Most of the product is in the form of castings, but a considerable quantity is made into tool steel and into the largest of blades for plate shears, and I am in a position to testify to the excellent quality of these products'.

The preface to the same article remarks :

> 'How long it is since the manufacture of crucible steel was commenced in this country I am unable to inform you, but it is known that long ago a considerable business was done in files and tool steel by one firm in this district'.

This must surely be a reference to the Calder Iron and Steel Works at Coatbridge, set up by David Mushet in 1800. The

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1 I am indebted for this information to Dr. George Thomson and I thank him for the trouble he has taken on my behalf. He also informs me that pieces of broken crucibles were still to be found on the Linlithgow site up to twenty years ago.

2 J. Riley, 'The Rise and Progress of the Scotch Steel Trade', J.I.S.I. (1885, vol.II), pp.394-395.

works was offered for sale in 1803 and the advertisement[1] lists, among the more normal ironworks plant items :

> '.... a steel casting house with fourteen cast steel furnaces capable of making four tons of steel weekly, together with a steel forge'.

Mushet was to leave Scotland shortly afterwards, but it is known that he supplied steel from these works to Peter Stubs of Warrington.[2] The steelworks was later mentioned in an advertisement of 1808, but does not figure in the inventory made in 1822.

This meagre evidence is the sum total which has come to light with regard to crucible activities in this country. It tends to confirm the other indications of the overwhelming importance of the Sheffield area in this branch of steelmaking operations, as, for example, in the statement that in 1856, in addition to the 2113 crucible melting holes in Sheffield, there were only some 245 holes elsewhere in the country.[3]

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1 Private communication from Dr. G. Thomson.

2 T. S. Ashton, An Eighteenth Century Industrialist (Manchester, 1939), pp.49-50.

3 J. Hunter (ed. Gatty), The History and Topography of the Parish of Sheffield in the County of York (Sheffield, 1869), p.214.

V The Scale of Production

Bearing in mind the importance of the cementation and crucible processes, with regard to the history of steelmaking in general, and to the development of Sheffield as the centre of the special steelmaking industry, it is a matter of considerable interest to endeavour to determine the scale of operations. This, however, is an extremely difficult task. Unfortunately, unlike America, France and Germany, Britain kept no official statistics of these trades. There are, in fact, no British records until 1868; these, when they do begin to be collected, only cover the Bessemer and Open Hearth production until the output of the electric steelmaking processes is incorporated, early in the twentieth century. There are some random estimates of blister steel and cast steel production to be found in the literature, but these fail by 1862. Any elaboration beyond this point must fall back on the indirect evidence and the interpretation of this relies on subjective judgement to a marked degree. An analysis of this type was put out some years ago[1] and, as was to be expected, its shortcomings were noted.[2] Nevertheless, it is an essential part of this study to bring together all the

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1 K. C. Barraclough, 'Production of Steel in Britain by the Cementation and Crucible Processes', Journal of Historical Metallurgy Society (1974), vol.8, No.2, pp.103-111.

2 Timmins, loc.cit., p.187, p.194, etc.

available information and, incorporating some further information which has become available since the earlier essay,[1] Fig.35 is now presented as a considered interpretation of the likely pattern of production.[2] It is in no way intended that it should be considered as definitive, but at least it indicates the trends which are reasonably clear to any serious student of the Sheffield story. It should also be made clear that it covers the joint output of the two processes, cementation and crucible steel melting; there is no way of separating them at this date.

The overall plot covers what must be considered as three separate phases. The first of these is the period up to 1873, where crucible steel was either the only steel available in ingot form - up to about 1860 - or was the only steel available in ingot form which was acceptable for critical purposes, for which wrought iron was unacceptable and Bessemer steel was looked on with suspicion. Set against the general growth of engineering and the prosperity of the early Victorian era, the rise in steelmaking capacity and output is not surprising. What might come as somewhat of a surprise, however, is the height of the peak output

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1 The import figures for Swedish cast iron into this country have kindly been provided by Miss Karen Hullberg of Jernkontoret in Stockholm, for the period 1855 to 1894.

2 The reasoning behind this presentation can be found in detail in Appendix YY.

in the early 1870s. This situation has been examined in depth.[1] Based on rate book evidence and the likely increase in furnace size, a figure of up to 50,000 tons extra capacity could well have been added between 1862 and 1872, in Sheffield. There is an estimated production figure of 51,616 tons of saleable cast steel from the Sheffield furnaces in the earlier year.[2] Losses in yield from ingot to bar were of the order of 15% or even somewhat higher, dependent on the final bar size. Taking this into consideration, the ingot tonnage in 1862 could well have exceeded 60,000 tons, giving a possible figure of around 110,000 tons of crucible steel ingots in 1872. In addition, the cementation furnace output for 1862 was quoted as 78,270 tons, almost 20,000 tons above that produced from the crucible furnaces. If the same trade continued - and under the conditions it might well have improved - a figure of 130,000 tons or so for the total production in 1872 is not unreasonable. Furthermore, it is not clear that 1862 was a particularly good year for trade; there could well have been some underutilised capacity at this date, which most certainly would have been taken up in the boom conditions of 1872.

The second phase is from 1874 to about 1890. This is the period when the growing steel industries abroad were

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1 Timmins, <u>loc.cit.</u>, pp.187-194.

2 J. Hunter (ed. Gatty), <u>The History and Topography of the Parish of Sheffield in the County of York</u> (Sheffield, 1869), p.216.

catching up with Britain. In addition, there were specific factors in the Sheffield trade which were altering the pattern, as has already been demonstrated. In particular, the production of large masses of steel, whether they were ingots for forgings or castings, was passing from the crucible process to the open hearth process. After the early 1880s it is doubtful whether there were any ingots made from crucible steel in Sheffield which required the contents of more than a few pots; the majority were the product of a single pot, as far as can be seen from the surviving records. The gradual disuse of numbers of crucible furnaces, in plants such as Vickers, Firths, Browns, Cammells and Jessops, must have reduced the effective crucible melting capacity considerably by 1890, despite the continued building of plant additions in the more specialised parts of the trade.[1]

From about 1890, the crucible furnaces found most of their trade in tool steels and high quality engineering materials, and it is to be noted that the postulated production levels in Figure 35 represent between 1% and 2% of the total British steel output for the whole of the period from 1885 to the outbreak of the war in 1914. A similar trend can be noted in America until about 1908, when it seems that the peak crucible capacity had been reached, to be supplemented by electric arc production; This came earlier in America than in Britain.

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1 Timmins, loc.cit., pp.194-199.

Comparison with the American figures is, indeed, interesting. There was no counterpart in America to the British peak in the 1870s; the American industry was too new. What is noticeable, however, is that the pattern in America, both in the growth of production and in the gradual fall in utilisation of Swedish materials, from virtual dependence in the early years, is very similar to that in Britain but came some fifteen years or so later in America. The secondary role of the crucible process in the production of special materials in Britain, therefore, was to be the primary role in America. The British curve, therefore, should be considered as being a composite derived from two different curves, each with its typical growth, maturity and decline characteristics. The earlier curve was an exclusively British phenomenon, covering the growth of the native crucible process, with a peak production around 1872 and subsequent decline.[1] Superimposed on this was the growing use of the process for the provision of special steels, particularly of tool steels and especially the 'Self Hards' and the later 'High Speeds', beginning to assume importance in the 1880s and peaking around the First World War period. This second phase was not only paralleled in America but also in France and Germany.

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1 Strangely enough, whilst doubts have been cast on the validity of the available estimates quoted in the literature, the curve plotting this information (see Figure A, Appendix YY) is a good representation of this first phase of the production.

VI Crucible Melting Costs

Information on crucible melting costs appears in a number of documents, which refer to operations over a period of about one hundred years. Both coke fired and gas fired furnaces are covered, and the evidence is presented in varying degree of detail, as can be seen in Appendix ZZ.

As far as furnace costs are concerned, Le Play in 1842[1] implied that a ten hole furnace required a capital outlay of £1500. The only other detail on such costs comes from seventy years later;[2] a sixteen hole furnace, coke fired, is then quoted as costing £1200. To obtain the same output of steel, some 25 tons per week, a modern type gas fired furnace would have cost £2000, whilst an 'old type' Siemens furnace is quoted at £3500.

A study of the operating cost data shows that the conventional coke fired furnace produced steel ingots at figures generally within the range of £6 to £8 per ton, over the whole of the period 1830 to 1914. It seems that the production of common steel for castings could be carried out more cheaply if so desired, presumably aided by the addition of aluminium to obviate the delay

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1 Le Play, loc.cit., p.665.

2 D. Carnegie and S. C. Gladwin, Liquid Steel - Its Manufacture and Cost (London, 1913), pp.477-478.

in 'killing'. In addition, there seems no doubt that the use of the gas fired furnace, particularly after the First World War when the price of coke had risen so steeply, could introduce substantial savings in melting costs, provided it could be kept fully occupied.

The only cost figures which are available for operations outside Sheffield are those from the Titanic Steel Works in the Forest of Dean.[1] These are significantly higher than the general average. The works was in an isolated area and transport costs would tend to be higher on this account. On the other hand, it has to be remembered that Mushet was operating complicated procedures on his early alloy steels which would, of necessity, have been expensive in fuel; even so, the record shows that experience brought with it some economy.

VII The Legacy of the Crucible Process

The tangible remains of the crucible process are now pitifully small. The only deliberately preserved crucible shop is that at the Abbeydale Hamlet. This may be taken as typical of the small establishments in the Sheffield area, originally built late in the eighteenth century or

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1 Sheffield City Libraries, Reference MD 1193-4.

early in the nineteenth. As commented earlier, it is essentially the same size as that described by Broling,[1] which he set up in Sweden after a visit to the various Sheffield steelworks. There are other remains, in various states of dilapidation, within the Sheffield area, but none are easily accessible to the public and many which have been described within the last decade[2] have since disappeared. At one time there were many walls containing row upon row of used crucible pots; most of these also have gone in recent years, with the clearance of old houses in the early industrial area of the town. The only crucible steel cutlery - or shear steel, for that matter - to be obtained is at inflated prices in antique shops.

There is, however, the intangible legacy. Had not the crucible process been invented in South Yorkshire, it is quite conceivable that the North East would have maintained its status as the steelmaking centre for a

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1 Please refer to Appendix II for details.

2 Details of identifiable sites in the early 1970s, together with some valuable instruction as to how crucible melting shop remains may be identified, may be found in R. Hawkins, The Distribution of Crucible Steel Furnaces in Sheffield, published as Information Sheet No.1 (Sheffield City Museums). In addition a number of the remains of crucible furnaces in the city were studied by D. Halley and form the basis of his unpublished R.I.B.A. Dissertation (1973), The Effects of the Crucible Steel Industry upon the Structure of Sheffield and a Field Survey of the Physical Remains.

longer period, and the growth of steelmaking activity in South Yorkshire might have been much slower. As things happened, Sheffield struggled to overcome its difficult geographical position, with its inherent transport problems, and made the most of its supplies of coal, refractories and water power to achieve a viable industrial base; nevertheless, quality of product and a satisfactory level of added value were essential to justify the cost of material imported into the area. This, in turn, involved a high degree of craftsmanship, which was inherited by one generation after another, passing from father to son in many cases, there being a pride in belonging to a tradition. Thus, by the time the pattern changed, and bulk steel production moved away from Sheffield to the ore fields, or to the coast to capitalise on cheap imported ores, the area was admirably adapted to take up the specialised production requirements. On the one hand, the provision of alloy tool steels was but an extension of the established experience on carbon tool steels and all the techniques were to hand. On the other hand, the provision of large forgings and castings to meet the growing needs of the engineering trades, and the defence of the country, involved only a growth in scale of practices which were well established in the larger works in the East End. These traditions still persist. Times have changed but the special steels and alloys needed for the most stringent applications, for the rotating parts of the modern jet engine or for the heart of the nuclear reactor, are still produced in Sheffield - still, be it said, by small scale melting units, when compared with the two to three hundred ton units common in bulk steel production. These small scale units have many modern facilities, with electric melting and vacuum or controlled atmospheres, but they have some similarities to the crucible furnaces in that specially selected raw materials are put into highly refractory containers and melted with as little contamination as possible, prior to being cast, with great care, into relatively small ingot moulds, so as to avoid major segregation problems in the resulting product.

12 THE CEMENTATION AND CRUCIBLE PROCESSES OUTSIDE BRITAIN

> 'The home production of iron and steel means more than giving employment to a portion of the population. In certain contingencies it renders a nation independent of foreign supplies at times when such dependence would cripple the most powerful nation in the world'.
>
> William Menelaus, 1875

I Introduction

Cementation and Crucible Melting - the 'Sheffield Methods' as they were generally known on the Continent, or 'les procédés Anglais' as the French termed them - were obviously accepted as being virtually a British monopoly, for a century or more beyond the date of Huntsman's invention. The cementation process, an essential pre-requisite to the crucible process over this period, was, as has been demonstrated, imported from the Continent but was made so much more essential here that it came to be looked on as an English process.

The possibility of parallel development elsewhere in Europe, in any sufficiently technically advanced area, was always present. For some reason, however, except possibly over Sweden, Britain gained an early lead and the attempts of the Continental powers and the United States to narrow the gap and achieve some degree of independence from

British imports provides an interesting study. The picture becomes clearer when the bulk steelmaking processes came on the scene and the tale of the lost pre-eminence of Britain in steelmaking in overall terms, first to America and then to Germany before the end of the nineteenth century, is too well documented to require any retelling.

The picture as to the older methods, first when they were the only rivals to the Continental 'natural steel' and subsequently when they performed the same kind of specialist function as they did in Britain, is much less clear and has received very little attention. Again, as in the British domestic scene, the survival of evidence is very patchy. Moreover, linguistic difficulties and geographical distance render the sifting of evidence from Continental sources more difficult. Nevertheless, some interesting information from a wide variety of sources has been collected together and has made possible a more complete account of early steelmaking abroad than has so far been presented. It has been considered logical to deal with the individual regions separately.

II Scandinavia

Steelmaking in Sweden, either by the cementation or crucible process, was always constrained by the lack of coal, there being no supplies of any importance within the country.

The main fuel available, wood, could be utilised in cementation furnaces but proved difficult to use in crucible melting, even after conversion into charcoal.

The history of cementation steelmaking, however, goes back a long way.[1] The first furnace was established at Davidshyttan in Dalarna as early as 1652, with a second at Eskilstuna in 1658. A furnace erected at Farna in 1664 continued in operation for 209 years. There was also a cementation steelworks at Nykoping in 1697. By 1764, the total of Swedish cementation furnaces was twenty one. Growth beyond that date gave 50 furnaces in 1820, 86 by 1850 and 93 in 1860. The total production was small, however; it rose from 888 tons in 1817 to 2352 tons in 1833[2] and gave a peak figure of 6970 tons in 1861. By 1880, there were only 18 furnaces still in operation, the Bessemer and Open Hearth furnaces having replaced the others.

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1 The bulk of the information on blister steel production is derived from C. Sahlin, 'Svenskt Stal', Med Hammare och Fackla, vol.III (Stockholm, 1931). This is printed as an individual publication within the book, with its own pagination. 'Brannstalstillverkningen' is Chapter IV, occupying pages 71-103; there are individual references to the various works in Chapter VII (pages 149-207). I am indebted to the late Torsten Berg, Esq. for taking me through the relevant passages. It has to be stated, however, that there is much information here that my lack of knowledge of the Swedish language prevents me from ascertaining.

2 F. le Play, 'Mémoire sur la Fabrication de l'Acier en Yorkshire', Annales des Mines, Serie 4me, Tome III (1843), p.675, put the Swedish production of blister steel at about 2400 tons per annum.

The design of furnace in Sweden developed on different lines from that in England, largely due to the need for wood firing. Sven Rinman drew up various designs in the latter half of the eighteenth century, many of which had vertical chests. By the early years of the next century, however, most furnaces were 'of the English pattern', although still fired with wood. Some furnaces, indeed, operated on imported coal, as at Graningeverken in 1753 or at Ramsbergs Bruk in 1859. As to size of furnace, Farna in 1746 was converting five tons per heat, whilst the capacity of furnaces working in 1850-60 seems to have been similar to the English ones. At Uddeholm for instance, in 1848 the original furnace held 55 skeppund per chest - a total of about 15 tons for the two chests - whilst the newly built furnace would contain as much as 150 skeppund per chest, giving a total of 40 tons. Wood consumption was from 640 to 675 cubic alnar (about 2500 cubic feet) per heat, the cementation medium being crushed birch wood charcoal.

Specific details are available with regard to blister steel production at Osterby.[1] The first cementation

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1 K. Hoglund, 'Making Steel by Cementation at Osterby Bruk', Fagersta Forum, No.3 (1951), pp.11-15. This was found, as a translation of unknown origin, among the miscellaneous papers of the Doncaster Archives. It is of interest as a report given by one of the last of the steelmakers and is reproduced in part as Appendix AAA by kind permission of R. T. Doncaster, Esq.

furnace there was erected in 1764, of the 'English type', fired with coal, largely as a result of the information brought back by Robsahm after his visit to the Newcastle area in 1761. In 1772 a new furnace, designed by Sven Rinman, was built. This burned wood and was in continuous use until 1908, being demolished in 1918. A third furnace was installed in the new steelworks - crucible melting having been introduced in 1869 - but the vibration from the nearby 50 cwt. hammer repeatedly cracked the seals on the chests and the furnace was therefore replaced by a fourth, built away from the main works in 1884, which continued in operation until 1918. Finally, due to the demand for steel, a fifth furnace was erected alongside in 1897 and this furnace was last used in 1929.[1] Details of the working of this furnace indicate it to have had a capacity of about 23 tons total, the chests having been constructed from firebricks. Specific points with regard to the Swedish process include the damping of the charcoal with a brine solution and the closing of the chests with a layer of ash on top of the charcoal, followed by a cover of sand mixed with half its bulk of finely crushed grog. The firing with wood appears to have led to the use of lower cementation temperatures than in Sheffield practice and the heats were correspondingly longer; the comment implying that ten heats per year per furnace was driving things along supports this. Osterby, in fact, was the

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1 It is now preserved on the site.

last cementation furnace to be used in Sweden.

The Uddeholm concern was engaged in blister steel production from 1818 onwards, when a furnace was commissioned at Munkfors; this seems to have been to Swedish design since a further furnace was erected in 1833 'under English supervision'. Two new furnaces were installed in 1842 and another two under Uddeholm control were built at Stjarnfors Bruk in 1844. There were alterations at Munkfors, involving the enlargement of at least one furnace, and a report of operations there in 1848 is available.[1] By 1850 annual production was around 5,000 skeppund (about 670 tons) from the two works. In 1862, a cementation furnace, designed by Lundin, which was producer gas fired with wood as fuel, was built at Munkfors and brought the annual production capacity up to around 1250 tons.[2] Thereafter, production soon fell, due to the introduction of Bessemer steelmaking at Uddeholm.

So much for Swedish blister steel manufacture; it

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1 G. Kraus, Jernkontorets Annaler (1848), pp.289-291. The title may be translated 'Report of Work at Munkfors'. A translation may be found in Appendix BBB.

2 A reproduction of the drawing of this furnace may be found in Figure 20. (Reference No. 23).

now remains to discuss crucible steel melting.[1] The interest shown by the Swedes in the utilisation of their bar iron has already received considerable mention and the reports of Robsahm, Andersson and Broling have been drawn on extensively in tracing the history of crucible steelmaking in Britain. Suffice it here to recollect that the two latter visitors both set up crucible steel melting shops in Sweden on their return. The Ersta Works, near Stockholm, was started as early as 1769, although not completed until 1780; nevertheless, it was the earliest crucible steelworks outside Britain known to have made satisfactory steel. It was obviously a very personal operation by Bengt Qvist Andersson, since it closed on his death in 1799. The works erected by Broling[2] commenced operations in 1808 and ran for almost thirty years. When it closed in 1837, the cause of its failure was really its uncompetitiveness in the face of English imports - it must be remembered that, although the iron was available, all the coal had to be imported and this placed a crippling burden on the economics. Broling died the following year.

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1 The information on crucible steel melting in the main derives from C. Sahlin, 'De Svenska Degelstalsverken', Med Hammare och Fackla, vol.IV (Stockholm, 1932), pp.35-134. My knowledge of the contents of these pages is far from complete; such as I have is due to the late Torsten Berg, Esq.

2 See Appendix II.

A further small works, making ingots of only 12 lb. in weight for use in cutlery production, was erected at Eskilstuna in 1818; this too closed down in 1837. Gustav Ekman commenced crucible steel melting at Lesjofors in 1840; production only seems to have been a few tons a year and this too had a short life, closing in 1851.

A works set up at Viksmanshyttan in 1859, however, had much better success. It was designed specifically to operate the Uchatius Process.[1] Local charcoal *smelted pig iron was used, granulated as it ran out from the furnace. The granulated iron was then reacted on* with pure Bispberg iron ore, with charcoal additions as necessary, in crucibles made from Belgian clay. The furnaces were coke fired, presumably using imported fuel, but it is noted that only 2.2 tons of fuel was needed per ton of steel, a very low figure compared with normal coke consumption in Sheffield. Specimens of the Viksmanshyttan steel were exhibited at the International Exhibition of 1862, where their excellence, particular as sword blade materials, was praised; the selling price was quoted as £50 to £60 per ton.[2] At the Paris Exhibition of 1867 even more praise was lavished on the products of this works; an as-cast ingot showed hardly any grain structure in the fracture; the forged bars showed an excellent fine

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1 Details of this process may be found in Chapter 8 (pp.325-8).

2 J. Percy, Metallurgy: Iron and Steel (London, 1864), p.803.

grain and their strength was the equal of the best British steel.[1] The author of the report went on to comment that this works seemed to be the only one to make a success of the Uchatius process, having found a reproducibility in the quality of the cast iron and a richness and purity in the iron ore, which would be difficult to match other than in Sweden. These conditions, apparently, continued to operate in favour of Viksmanshyttan, since photographs of the granulation of the cast iron and the teeming operation from crucibles dating from as late as 1929 have been reproduced.[2] Production grew steadily and additions to furnace capacity were made in 1898, 1906 and 1912. By 1915, a peak annual output of just over 2000 tons was reached, as can be seen from Table VIII. In view of the success at Viksmanshyttan, it is strange that two other works, built to operate the same method, both failed within a few years. These were the Hallefors Works (1859-1863) and the Killafors Works (1861-1868). It is not clear when Viksmanshyttan ceased operations on the Uchatius process, but it was some time in the 1930s.

The works at Osterby, which, as has been noted above, was founded in 1764, did not take up crucible melting until 1869. For the first ten years, operations were on a co-operative basis with a number of the adjoining works.

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1 S. Jordan, Revue de l'Industrie du Fer en 1867, vol.4 (Paris, 1871), pp.314-315.

2 Sahlin, loc.cit. (Degelstalsverken), Fig.25 (p.84) and Fig.27 (p.88).

During this period, Baron Tamm used his contacts in the Sheffield steel trade to acquaint himself with the modern techniques and he adopted many of these, including a mechanical press for making crucibles from clay on site. The furnace used was the Siemens regenerative type, the chamber taking six crucibles, but modified by Lundin to operate with a wood fired gas producer. Under co-operative management, output was small, being less than 50 tons per annum. From 1880, under full Osterby control, matters improved and additions were made to the plant. The production in 1886 is quoted as 165 tons.[1] By this time the furnace had two fusion chambers, each capable of taking ten crucibles. The producer had been modified to coal firing. The blister steel used was sorted into six categories according to fracture; the melting of the correct batch with sufficient spiegeleisen to give 0.2% manganese in the final steel gave carbon contents controlled to within 0.1% in the product. The yield of ingot was 96.3% of the metal charged. 200 tons of ingots were made in the year by 1890; 500 tons per annum was reached in 1899. Between 1911 and 1922, when the quoted production figures cease, output was between 500 and 950 tons per annum (except for a slump to 380 tons in 1919). From 1890, incidentally, it is clear that blister steel was no longer the main charge to the crucibles; from 1910, blister steel output fell and from 1917 to 1929 was less than 100 tons per annum. Crucibles seem to have been made from a clay

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1 C. Y. Hermelin, Jernkontorets Annaler, vol.xlii, pp.338-343, as abstracted in J.I.S.I. (1888, vol.I), pp.330-331.

similar to Derby clay, mixed with a Dutch substitute for China Clay and powdered coke, in the proportions of 210 kg to 35 kg to 6 kg 'according to the English method'. Each crucible was used three times, the weight of charge being reduced by 1 kg each successive melt. The weight of ingot using a single crucible was from 20 kg to 25 kg (44 to 55 lb.); ingots of 85 to 350 kg (180 to 770 lb.) were cast from time to time as required. Coal utilisation was about 2.25 tons per ton of ingots. In 1886, steel with 2% chromium was being produced. From 1890, tungsten steel (presumably of the 'Self Hard' type) was produced. From 1903 onwards, high speed steel, to the Taylor White formula, was made at Osterby, as indeed it was at Viksmanshyttan.

Two other firms subsequently undertook the manufacture of alloy tool steel in crucibles. Soderfors operated a producer gas fired furnace from 1904 to 1916, producing in total some 3200 tons of ingots in this period, the crucibles taking 45 to 50 lb. each. A similar works at Fagersta, operating between 1905 and 1912, made some 450 tons of ingots.

The most interesting crucible steelworks in Sweden, however, seems to have been the Karlsviks Mitisguteri in Stockholm, set up in 1884 to operate the patent taken out by Carl Wittenstrom, by which steel was made dense and sound by the addition of aluminium. The product was used for castings and the method became known as the 'Mitis Process'.

The furnace was unusual in that it was fired with naphtha, or petroleum, with a combustion chamber heating three holes, each containing two crucibles capable of holding about 40 kg (88 lb.) of metal. Castings were made from steel with the normal carbon content (0.4% to 0.8%), but also from very low carbon charges, virtually remelting bar iron, with as little as 0.1% carbon. The killing with up to 0.1% aluminium allowed sound castings to be obtained, free from blowholes, regardless of carbon content, and without the need for 'killing with fire'. This gave a very flexible operation combined with a marked saving in furnace time.[1] Production at this works seems to have continued until about 1924.

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1 It is of interest that the Mitis Process seems to have had considerable success in America. Sahlin mentions its use at Worcester, Massachusetts. He also states it was operated at the Canal Steel Works in Sheffield and at locations in Belgium, France and Germany. Elsewhere it is reported that it was in operation in five American steelworks in four different states, as well as in Sheffield, France and Belgium. This statement derives from a private communication from the U.S. Mitis Company, dated 7th January 1889, to H. M. Howe (see his Metallurgy of Steel (New York, 1892), pp.308-310). Its association in America with Nobel's petroleum furnace (according to the available drawings, the Swedish furnace was similar) and its use at the Milwaukee Cast Steel Foundry is described in Foundry, vol.36, pp.130-132, quoted by D. Carnegie and S. C. Gladwyn, Liquid Steel: Its Manufacture and Cost (London, 1913), pp.103-105.

As far as Norway is concerned, Le Play put the production of blister steel at barely 500 tons per annum in 1842.[1] The only description of any specific cementation operation which has been found is in respect of the silver mines at Kongsberg.[2] Here in 1765 there was a charcoal fired furnace with three chests, holding about 10 tons per heat. The cementation medium was beechwood charcoal. The furnace was used infrequently, perhaps once or twice a year, simply to produce the steel required in the mining operations. There was at least one Norwegian crucible steelworks, since the one at Naes, near the southernmost tip of Norway, is currently being restored.[3] It appears that there had been a blast furnace and a bar iron forge on this site since 1738 and that by the time the crucible shop was erected in 1859 there was also a cementation furnace. The furnace had six holes. From 1859 to 1910, steel production was based on the use of local bar iron and cast iron; after the blast furnace was blown out in the latter year, charges were made up from scrap and wrought iron with charcoal, until closure of the plant in 1940. Steel from Naes was exhibited at Paris in 1867 and it was said to be of excellent quality, produced by the English method from their own iron. They were said to have three cementation

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1 Le Play, loc.cit., p.676.

2 G. Jars, Voyages Métallurgiques, vol.1 (Lyons, 1774), pp. 174-176.

3 A report on this works, with photographs and drawings of the crucible shop, also showing drawings of ingot moulds used, is to be found in 'Noen Norske Jernverker', Jernkontorets Berghistoriska Utskott, Forskning Serie H, Nr.15 (Stockholm, 1977), pp.13-21. I am obliged to Alex den Ouden for bringing this to my attention.

furnaces and eight crucible holes.[1]

III France

The development of the manufacture of steel in France was surveyed in 1846 by Professor le Play[2] and the later eighteenth century has been the subject of a recent study.[3] It is a story full of paradoxes.

There was an early tradition in the making of 'natural' steel in the Isère and the Dauphiné, and the 'Méthode Rivoise' had some fame in the late seventeenth and the eighteenth centuries as a rival to the steel from Austria. As far as cementation steel is concerned, it is probable that it was known in France during the first half of the seventeenth century, since there are records of its use in

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1 Jordan, loc.cit., pp.315-316.

2 F. le Play, 'Mémoire sur la Fabrication et le Commerce des Fers à Acier dans le Nord de l'Europe', Annales des Mines, 4me. Serie, Tome IX (1846), pp.113-306. What is not clear from the title is that Part II of this report (pp.209-272) is nothing less than a history of cementation steelmaking in France; for this reason, most researchers appear to have overlooked its importance.

3 J. R. Harris, 'Attempts to Transfer English Steel Techniques to France in the Eighteenth Century', Business and Businessmen (Liverpool U.P., 1978), pp.199-233.

both North Germany and Italy at this period. The earliest firm records from France come from around 1675.[1] The most renowned work on the cementation process, however, is that of Reaumur[2] published in 1722. For its date it is a remarkable and often brilliant exposition of technological investigation but, quoting le Play[3]

> 'as regards the choice of iron for making steel, he made a categorical pronouncement that most of the provinces of the kingdom could furnish in abundance those irons eminently suited for conversion to steel and that such irons came, in particular, from Hainaut, Nivernais, Berri, Burgundy, the Dauphiné, Bearn, Angoumois, Perigord and Brittany.
>
> These assertions were given with the authority due to an eminent scientific celebrity; they resulted from a long series of trials undertaken for the public good, with special support from and at the expense of the government; they flattered national pride and at the same time offered a brilliant prospect to the particular interests of all these provinces. They were accepted by everyone without question. The works of Reaumur, which earned him a pension of twelve thousand livres,* were henceforth followed as an infallible guide to all who would undertake the manufacture of cementation steel in France. The authority which Reaumur's book has

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1 N. Lémery, Cours de Chymie (quoted by T. A. Wertime, The Coming of the Age of Steel, p.205); A. Félibien, Des Principles de l'Architecture de la Sculpture, de la Peinture et des autres Arts qui en dependent (Paris, 1676), p.189.

2 R. A. F. de Reaumur, L'Art de Convertir le Fer Forgé en Acier (Paris, 1722). There is a translation in English by Anneliese G. Sisco, published by the University of Chicago Press in 1956.

3 F. le Play, loc.cit (1846), pp.214-216.

* This presumably refers to the livre tournois which was worth around 10d throughout most of the eighteenth century, making Reaumur's pension about £500, a not inconsiderable sum at the time, however.

maintained to the present time, coupled with the errors to which it has constantly given rise is, without contradiction, one of the most singular incidents presented by the whole history of French metallurgy. The influence exercised by the works of Reaumur still persists among those who have not had the occasion to become involved in the study and practice of the workshops. So much is this so that recently published reports and special treatises have purported to show that the superiority of the English steelworks and the inferiority of the French ones arises from the English having taken the trouble to put into practice the precepts of Reaumur, whilst the French have allowed them to fall into neglect.

This would have been completely inexplicable as far as I am concerned had not a vast quantity of official documents allowed me to follow the divers phases of the development and decline of the numerous steelworks established in France during the last century and if I did not see the present day adversaries of tariff reform, who regard the past as though it had never happened and pose the questions in the same terms as they were put at the start of the last century'.

Later, in concluding this part of the report, he has this to say :[1]

'Up to the present day it has not proved possible to find within the kingdom the raw material suitable for the manufacture of fine steel. The misfortunes which have been experienced by all the steelworks which have been established in France for the last century and a half stem essentially from the erroneous opinions set out by Reaumur and sustained by official trials with regard to the steelmaking characteristics of the indigenous irons. The real successes, which have only recently been

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1 F. le Play, loc.cit., (1846), p.273.

> obtained in France,* that is to say the only ones which could hold up for a single day under conditions of free competition, are due, purely and simply, to the adoption of a method of operation on which, over two centuries, the prosperity of the English steelworks has been founded, namely the employment of the steel irons produced in the Northern lands and, in particular, the use of the best grades from Sweden'.

In fairness to Reaumur, it must be stated that his researches were painstaking and his writing and presentation a model of clarity.[1]

Reaumur spent a considerable amount of time and effort on investigating the various cementation media; that his report was given serious consideration in England is evidenced by the interest shown by William Lewis in his projected history, written about fifty years later, which

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* James Jackson set up a works in France in 1815, originally using Swedish iron; he was subsequently prevented from doing so but, by 1838, his sons had succeeded in returning to such practices; this was the recent success (see p.566).

1 C. S. Smith, in the introduction to the translation of Reaumur's treatise (loc.cit., p.xx) states :

'Books in which theory and practice are presented in a balanced and integrated way are rare enough even today and the modern metallurgist may well read with respect the work of Reaumur who, over two hundred years ago, attempted to combine the science and art of metallurgy. He was, in fact, one of the first writers on any topic who can be called an applied scientist in the modern sense and he has the additional distinction of being the first to produce a significant book on iron and steel'.

summarised Reaumur's work on this particular aspect.[1]

Reaumur's researches covered other aspects, including some most elegant work, with well drawn illustrations, on the fractures obtained with various irons; he investigated the heat treatment of steel and made all the correct moves; he surmised that the conversion of iron into steel was due to it taking up some essential ingredient by a diffusion process and in this he was correct - that he considered the ingredient to be 'sulphurs and salts' was only in keeping with the theories of his time. The second part of his treatise, dealing with the decarburisation of cast iron, formed the basis of the malleable iron casting industry, a most important development.

With regard to the manufacture of cementation steel, however, he had made his categorical statements and he was soon called upon to substantiate them in a practical manner. So a company with letters patent was established under his management: the 'Manufacture Royale d'Orléans', with a main works at Cosne, was established to sell steel, which did not yield anything in quality to the best then available, at 10 sols per pound, stamped with the mark of

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1 W. Lewis, <u>The Mineral and Chemical History of Iron</u>, written about 1775-1780. An unfinished manuscript in 6 volumes is preserved in the Cardiff Public Library, Reference MS.3.250. The above mentioned summary appears in Volume V, folios 107, 109, 111 and 113 and may be found in Appendix I.

the particular works.[1] The judgement of the users of this steel, however, did not concur with that set down in the manufacturer's prospectus; the company exhausted its capital and, within twenty years of the publication of Reaumur's treatise, the works at Cosne was abandoned and France continued to seek the steel it needed from England. At this time, only two works, situated near the Swiss border, working with the iron from Franche Comté, could deliver steel which met with approval; these also, within a few years, ceased their operations.

Into this stagnating situation came Michael Alcock from the Birmingham area.[2] He petitioned for a works to be allowed for the manufacture of edge tools, file making, button and buckle production - in fact the typical 'Birmingham Toy Industry' which, of course, involved the making of steel. He soon moved from his first site to La Charité-sur-Loire in 1757; in 1762, however, he left and was succeeded at La Charité by Sanche and Hyde; the latter was another Englishman.[3] It is not clear, however, whether any steel was actually produced during this period. In 1765, whilst Alcock was setting up his sons in another works at Roanne, he reported to the minister Trudaine that he had tested all the French

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1 F. le Play, loc.cit. (1846), pp.217-218.

2 J. R. Harris, loc.cit. The story of the Alcocks appears on pp.206-208.

3 If not, he was, at any rate, of English ancestry.

steels and, far from finding any to be good, none was worthy of the name of steel, pointing out that even the iron from Berri, possibly the best in the kingdom, was grossly lacking in homogeneity, not only from one bar to another but also within adjacent pieces of the same bar. In 1769, however, from the works at Roanne, Alcock reported that he had produced some good blister steel which was well thought of by the craftsmen; the following year a report claimed that his steel was equal to the best English cementation steel. Nevertheless, little was subsequently heard of these activities.

Trudaine, having assessed the situation in 1765, decided on a course of action which covered the collection and dissemination of information on the English methods of cementation, the encouragement of those firms which produced a better grade of steel, preferably from native iron, but not excluding the use of imported iron if such were necessary, and the importation of English artisans.[1] Trudaine's comments on this last point are interesting. Even though many imported English workers proved to be lazy, ignorant, insolent, given to drink and, in short, unreliable, a few were worth their weight in gold. He would, therefore, pay the expenses of their journey, support them until they found work and, if necessary, enrol them in the workshops

1 H. T. Parker, The Bureau of Commerce in 1781 and its Policies with respect to French Industry (Carolina, 1979), p.134.

in St. Étienne.[1]

It was in these circumstances that Gabriel Jars received his commission in 1765 to visit the English steel-works to determine the reasons for the high reputation of their products.[2] As a result, his report clearly set down the essential requirements :[3]

> 'The one and only iron which has been found fit for conversion into steel is Swedish iron. Many trials have been made with iron produced in England, but none of them has ever provided a steel of sufficiently good quality.'

> 'Only powdered wood charcoal is used for the conversion of iron into steel; no use is made of oil or of salt'.

It seems inconceivable that such clear evidence should then have been ignored in France; what is utterly incomprehensible, however, is that Jars himself should subsequently be given charge of a small works at St. Antoine near Paris with instructions to put into effect what he had learned in England but with an insistence that he should use only indigenous irons. Jars himself left no comment on these

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1 Monsieur de Trudaine concernant les ouvriers anglais, 1765. Ref. F^{12}. 1316.

2 It was at this time that the French cutlers and edge-tool makers willingly accepted Huntsman's steel at a time when his countrymen rejected it. So it was that their superior products became an embarrassment to the Sheffielders!

3 Jars, loc.cit., p.222.

operations; his brother only published a furnace design from the works without further comment, but documents proved that some two hundred thousand livres were wastefully used on this futile experiment.[1] Nevertheless, the report put out by Jars had its leavening effect in that it contained furnace diagrams as well as the instructions, for those who would read, in their fight against officialdom, vain as this proved to be in most cases.

It was about this time that the Count de Broglie was commissioned to set up a steelworks in Angoumois, to use the iron which Reaumur had singled out for honourable mention in his treatise. He set up his establishment at Ruffec in 1769, with Duhamel in charge of operations. With an annual endowment of fifteen thousand livres,[2] it battled against the obstacles set by its terms of reference for fifteen years before closing down in 1782. But it was only one of several: those in Franche Comté, under M. Mongenet, in Berri, under the Duc de Charrost and in Burgundy, under Buffon, were equally unsuccessful.

The steelworks at Nerouville, however, was set up in 1770 and it was clear that the founders set themselves out to apply the conditions which Jars had found in England. This works, on the canal from Loing which brought in the refractory materials and the coal from Forez and Auvergne,

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1 Le Play, loc.cit. (1846), pp.221-222.

2 Livres turnois; for detail see above (p.536).

originally employed imports of Swedish iron exclusively. Samples of such steel were tested and found to be of first quality and equal to the English material in 1775.[1] Just to make sure, it would seem, similar tests were carried out in 1778, with the same conclusions.[2]

The cementation furnaces had been carried to sizes which bore witness to the activity and the regularity of their production and which had not been surpassed before, even in England. One of their furnaces took 40 tons of bar iron at one time. Such prosperity, based on the use of foreign iron, acutely stirred public opinion. Grignon, a former forgemaster, whose writings and position made him the foremost authority in this field, believed he should oppose the direction in which French industry appeared to be moving, which he did in several memoires; supported by the ideas put forward by Buffon, he received a government commission in 1779 to carry out comparative trials with French irons alongside those from Sweden, Siberia and Spain. He chose the works at Nerouville for these trials and assembled there supplies of iron prepared by the various groups of forges throughout France, together with but single samples of both Swedish and Siberian irons, taken at random from commerce and probably

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1 Extrait des Registres de l'Académie Royale des Sciences, 12 Août 1775, Reference F[12]. 1303.

2 Extrait du Procés Verbal des Essais d'Acier Cements fait par ordre du Gouvernement par M. le Chevalier Grignon, 5 Mars 1778, Reference F[12]. 1303.

nothing but ordinary quality which would not have been considered as suitable for steel by the English.[1] The outcome was obvious; what is surprising, however, was that the management accepted the results, in spite of their own experience. From this moment, the steelworks at Nerouville began to decline and was closed about 1792. In 1793 one of the hammers, which had not yet been demolished, was brought back into action at the start of the remarkable epoch which the French Revolution opened up for the steelworks.[2]

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1 The full details of these trials were included in a report given as an appendix to Grignon's translation of Torbern Bergmann's work on iron and steel (entitled '<u>Analyse du Fer</u>' in translation). A translation of pp.234-251 of this report, giving practical details of the cementation technique used, may be found in Appendix CCC. The remainder of the report, which deals with the methods of testing the materials and covers a further 30 pages, has not been considered as of much interest. Suffice it to say here that the iron purporting to be Swedish was stamped S.I.D. which does not, according to Bo Molander, the expert in such matters and to whom I made enquiries, appear in any Swedish list of the time. It is clear from the report that it was purchased in Le Havre as Swedish iron but its origin was unknown. It appears, in fact, that it could well be a Russian iron since there is a slightly later reference to one such marked D.S.I., an inferior grade selling at £26 per ton, at a time when the best quality Russian iron, CCND, sold at £37 per ton and 'Hoop L' and 'Double Bullet' cost £40 per ton (A. Rees, <u>Cyclopaedia</u> (London, 1819) - article on 'Tilting of Steel'). It seems inconceivable that, when the grades of iron used in England were well known from the writings of Gabriel Jars and others, such a material should have been purchased at random for these trials, unless, of course, there was no intention of placing the French irons at a disadvantage.

2 The information on Nerouville, like most of the above narrative, is taken from Professor le Play's 1846 report.

It is of the steelworks at Amboise on which most information is available, however, at this time.[1] This was eventually by far the largest cementation steelworks ever considered in the eighteenth century. Sanche, who had conducted the manufacture of cutlery, edge-tools and 'jewellery' at La Charité-sur-Loire for some twenty years, had succeeded in making satisfactory steel, having previously imported his requirements and, in 1782, supported by capital from Patry, he set up a steelworks at Amboise on the site of a former file factory. Here, using Swedish iron, he succeeded in making good steel and in May 1783 applied on these grounds for the privileges and capital which they needed to develop their enterprise. An undated document signed by Sanche, indicating his success with Swedish iron and iron from Berri, gives his procedure. This text, in translation, can be consulted in Appendix DDD. As soon as these negotiations were under way, however, the manufacturers were to find themselves embarrassed on the question of the use of indigenous irons; having pointed out that their production was entirely based on foreign iron, they were given to understand that this condition prohibited any hope of success in their application. The reply

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1 In addition to the information available from le Play, I have drawn extensively in this section on a number of original reports, copies of which were kindly provided by Professor J. R. Harris; I am also indebted to him for a number of private communications in this particular field.

reads rather strangely :[1]

> 'They and only they had succeeded in making the steel which the English called cast steel and which could serve for all kinds of superfine work, such as the dies for coins or medals, for surgical instruments, razors or all kinds of cutlery. There were not to be found in it any slag or stringers or grains of iron. These more perfect materials could not be made except with Swedish iron and the English would use no other. With French iron converted in the same way, it would only give a very rough and difficult to work material and Sanche and Patry could not hope to make use of the nation's iron for their purpose except after a series of trials and tests'.

The reference to cast steel can, however, be explained in the light of other evidence. Later in these negotiations, Sanche was called upon to provide a mémoire giving his proposed procedures for official consideration. In this document it is stated that only Swedish irons and those from two particular forges in Berri are suitable for conversion into fine steel, commonly called 'cast steel' by the cutlers. It is clearly pointed out that the French irons must be refined in a very careful and particular manner and forged so as to be completely fibrous and it is also pointed out that this will add up to 10% to the cost of the iron. There is reference to Swedish iron of the mark 'KW', this being from a purer ore and thus being a superior material - it is noteworthy, however, that it is not a grade which ever seems to have been used in England. It is also pointed out that the iron

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1 Mémoire addressed to the General Commissioner of Finances from Amboise, 9th May 1783, quoted by Le Play, loc.cit. (1846), p.234.

should not be more than 5 to 7 lines[1] thick, since iron which is too thick may give trouble due to incomplete conversion in the furnace.

The method of cementation is described in detail. In the first place, the iron bars were cut to the correct length for the chests. They were then put into a large lead lined tank full of river water into which 15 to 20 pounds of English salt or a similar quantity of sal ammoniac had been dissolved. When the bars were well soaked they were placed into a further chest containing a well milled mixture of

One part ox horn or hoof, roasted and powdered
One part of soot
One part of wood charcoal, powdered.

Whilst the bars were being coated with this cementing mixture, a bed of a second and main cementing mixture was placed in the cementation chests, made from the following mixture :

One part of wood charcoal, well powdered
Two parts of soot

or a mixture of this with three parts previously used cementing mixture, well sieved and crushed.

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1 The line was a measurement of an indefinite nature but a French Dictionary of 1822 states it to be one twelfth of an inch. (Elsewhere it seems to refer to one tenth of an inch, however).

The iron bars were carefully placed on the bed of cementing mixture in the chests, with the bars 4 lines apart, followed by another layer of the cementing mixture and another layer of bars, and so on until the last layer of cementing mixture almost filled the chest. It was then good to cover the last layer with a bed of fine sand or crushed brick prior to laying flat fireclay tiles over the filled chests and luting the whole with a mixture of yellow clay mixed with horse manure. The use of trial bars, in the usual manner, is described. The heating and cooling of the furnace was to the standard practice. The method of forging needs to be quoted in full :

> 'If it is wished to make fine steel, the bars are taken and forged to 18 lines wide and 6 lines thick and then 9 to 11 bars are put together, the one to the other, at a length of about two and a half feet; they are all then forge welded together in the form of a bloom which is then taken down to 18 lines by 6 lines. These bars are then put into the furnace in the same way as the iron bars which were originally converted into the steel which is called 'No.1'. In this way the steel takes on an extra degree of fineness and can be called 'No.2'. To make still finer steel, suitable for making razors, lancets and other surgical instruments, it is necessary to treat 'No.2' steel in the same way, to forge it, put it into the furnace for a third time with the same cement and the prescribed precautions and from this is produced the steel which has an extremely fine grain which is called 'No.3' or <u>'cast steel'.</u> '.

From this it is quite evident that the French, being aware of the high reputation of 'cast steel', were attempting to produce material of equal quality by whatever means were available - a parallel case of 'German steel' being produced by Bertram at Blackhall Mill from blister steel by a forging operation.

Within three weeks of the application by Sanche for official assistance, he was obviously making a serious attempt to use French iron; by the end of May he had produced a steel 'marked with the Cross of Lorraine',[1]

> 'which is superior to most of that from England ... whose sole defect is that it lacks a little in cleanness and that only arises from lack of experience among the workers who are not used to forging it. I flatter myself that they will not be slow in acquiring the desired degree of perfection'.

Soon afterwards he reported :[2]

> 'Splitting is a defect which has previously shown the French irons to be unsuited to conversion to steel; it is true that this is a general defect but I have succeeded in removing from it the arsenical matter which no doubt occasions it. For this reason I am eager to pass on to you the results of this newest trial. In the test which I have made, it has been remarked that it forges and welds very well, not giving any cracks, taking the most hard temper possible and giving the finest possible grain. The only thing which I think I have seen of any detriment is the presence of a few small slag patches which only derive from the lack of attention general in iron forges and I propose to remedy this important defect'.

It is inferred from this that he had reforged the iron prior to cementation and this may well be the origin of his requirement of special treatment by the iron forgers to which he made reference in his proposed method of manufacture to which

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1 Sanche to the General Commissioner of Finances, 5th June 1783, quoted by Le Play, loc.cit. (1846), p.235.

2 Sanche to the General Commissioner of Finances, 21st June 1783, quoted by Le Play, loc.cit (1846), p.235.

reference has already been made.

As a result of work carried out on the various samples of steel which Sanche supplied and examination of his proposals, an official inspection was carried out a year later.[1] The inspectors were none other than Vandermonde and Berthollet. They found the steel to be generally satisfactory, to forge well, to harden satisfactorily and to give a high polish. They commented that his method differed from those so far published by Reaumur, Wallerius and Jars and all others of which they had knowledge and that they did not understand the construction of his furnace; nevertheless the results were obviously satisfactory when carried out on good iron. They concurred with Sanche in that they recommended that the iron forges take more care in the preparation of their iron bars for steelmaking. On the other hand, they were critical of the use of the term 'cast steel', in that it was merely a fine grained material, which nevertheless contained some cinder, and could not be used where a combination of extreme hardness and extreme cleanness was essential. This could only be obtained by fusion of the metal to remove the cinder completely.

Their final conclusions were somewhat qualified in their recommendations :

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1 Procés Verbal, 15th June 1784, Reference F^{12}.656.

'Following our long conversations with M. Sanche, the local inspection of his works and the examination of his apparent resources, which not having inspired us with a sufficient degree of confidence in the success of the immense establishment proposed in his project, the precaution taken by the Minister of regulating the encouragement accorded to the provision of a specific quantity of steel which he can verify having produced on the premises appears to us very wise. This encouragement should be sufficient for him to find the necessary resources .... It is only necessary for him to produce 300 milliers of steel per year at the most, a quantity which he can easily exceed .... and this appears to us to offer a sufficiently well founded hope of success'.

There followed a further officially supervised production of steel, with fully documented samples being given official stamp marks, with their later transfer to Paris and their submission to various master cutlers and filemakers for their assessment and at last, in 1786, Sanche was awarded the privileges which he had sought and the works at Amboise became 'The Royal Manufactory of Fine Steel and Cast Steel' - by then, true cast steel was produced, since a printed 'Procés Verbal' of that date, enumerating the various items of production at the Royal Works mentions both 'Superfine steel, so called cast steel, marked with the letters S and C and a sun surmounted with a fleur de lys' and 'Real cast steel, marked S & C CAST STEEL'.[1] In view of the stress which had so far been laid on the use of French iron, it is, however, remarkable that another contemporary inspection

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1 Baron de Dietrich, Procés Verbal, August 1786, Paris, September 1786, Reference F^{12}.656.

of the works revealed that, of the 280 milliers (125 tons) of bar iron in store for conversion to steel, some 90% was of Swedish origin.[1] From the same document, it appears that only eight cementation heats had been made in the previous ten months, four of them from a very small furnace (the weights varying from 2983 to 3390 pounds) and four from the large furnace (with weights from 28129 to 31950 pounds). There are drawings attached to this report which are stated to be of the furnaces proposed by M. Sanche, but not those actually in present use; these are none other than the drawings made by Gabriel Jars of a furnace in the North East of England (probably at Swalwell) in his Voyages Metallurgiques.

> 'The establishment now went forward on a grand scale; six furnaces, each containing 32000 to 36000 pounds at each heat were constructed, together with all the necessary shops, and six more furnaces were to be added shortly. Six hundred workers were already occupied at these useful tasks and the number would continue to grow according to the needs'.

This was written a year later.[2] However, there were beginning to be doubts as to the size of the operations and a year later Berthollet makes these observations :[3]

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1 Report by Marin Renaultz, Inspector of Manufactures, 26th May 1786, Reference F^{12}.656.

2 Document dated 17th July 1787, quoted by Le Play, loc.cit. (1846), p.238.

3 Report by Berthollet dated 9th July 1788. F^{12} 656.

> 'From the start, the establishment was considered on too big a scale. Originally it was proposed to make six million pounds of steel per annum[1] but this is more than the total French trade ... The Company saw too late the gap between their production and the demand; as a consequence, they have discontinued the building of six furnaces which had already been commenced by M. Sanche and he has restricted to a smaller number the forty hammers which he intended establishing near the Loire. He thus has had to suffer considerable losses through his own negligence of the true facts .... He has, however, to meet the established price for steel with his own product if the establishment is to succeed .... It is, however, difficult to discover the real price of German and English steel since those engaged in this commerce have their own interest in keeping it hidden. There are many contradictions in such information as we have managed to procure but it appears that German steel costs about ten sols and common English steel from eleven to twelve sols; it appears to us that steel from Amboise could be sold without loss at nine sols.... One cannot but wish that those who formed the company had not allowed themselves to be seduced by exaggerated hopes but, whilst the establishment is become much less advantageous to them than they had imagined, it no less merits the protection of the administration and provided it can survive it will be of real value to France. The administration should, in its wisdom, carefully consider the demands made by the company and accord it these favours which in no way would be prejudicial to the national industry and should be in proportion to the utility of the establishment. It is to be desired that the Marine Department should consent to nominate Amboise as its supplier if they can so obtain steel at a price equivalent to that of imported steel, as the administrators of the factory have claimed'.

It seems that, despite his annual 'encouragement' of some twenty thousand livres,[2] Sanche was beginning to fight a losing battle. He gave up at the beginning of the Revolution and was

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1 About 2700 tonnes, equivalent to 14 heats on each of the twelve proposed cementation furnaces a year.

2 This quite definitely is 'livres tournois', making the sum equivalent to about £800 at that time.

succeeded by Decluzel who obviously had to travel the same hard road; eventually, discouraged after innumerable unfruitful attempts, he demanded help from the Directory both in monetary terms and in their direct intervention with the forgemasters in an attempt to improve the quality of the French irons:[1]

> 'Since I first commenced to make steel at Amboise I saw with a sad heart that the indigenous irons were not suitable for cementation and that it was necessary to import those of Sweden. I have made tests with virtually every French iron and, persisting in my search, have purified them within my own works, which gave a better result. From this, I recognised they were lacking care and a little further working in the iron forges in the various cantons of the Republic. I have managed to obtain a little from the mines of Berri from which I produced steel as good as that from the Swedish irons. It has become clear to me, however, that it is difficult for me to persuade the forgemasters to purify and hammer their irons as is necessary if they are to provide good iron for steelmaking. It is necessary, therefore, that the Government should take steps in this matter so as not to have to go back to Sweden in order to be able to make steel suitable for all purposes in France'.

His appeal had little positive result and he withdrew from the battle in 1806. His successor, Saint Bris, seems to have had even less success since a year later there were only forty to fifty workmen there.[2] Files made there were so poor that they could not be sold and by 1816 Saint Bris was seeking to import steel.[3]

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1 Letter dated 14th Ventose, Year 8, quoted by Le Play, loc.cit., p.240.

2 H. and G. Bourgin, L'Industrie Siderurgique en France au Debut de la Revolution (Paris, 1920), p.163.

3 J. R. Harris, loc.cit., p.217, quoting document F^{12} 2219.

Such, then, is the history of French steelmaking in the eighteenth century, over a period in which the combination of the fully established English cementation steelmaking techniques and the methods of handling blister steel were transferred from the Derwent Valley to Sheffield, and which, combined with the development of Huntsman's crucible process, were firmly establishing England's superiority in steel production. These processes, together with the radical modifications in iron production, following the work of Darby and Cort, were the 'procédés Anglais', about which the French were so eager to learn. At the same time, much of the study of the nature of iron and steel was being carried out in France, culminating in the publication in 1786 of the essential part played by carbon. In view of all this, it is all the more inconceivable that, time after time, officialdom was able to stifle the best efforts of Sanche, the owners of Nerouville and several others, including, it would seem, Jars himself, at a time of such enlightenment and despite the first hand evidence provided by Gabriel Jars. Particularly is such a situation inexplicable when it was clearly to the advantage of the country's main commercial rivals across the English Channel.

It could well be there were unexpected technical difficulties and misunderstandings; moreover, the blind investment of capital such as that by Sanche was made without any true understanding of the commercial and technical possibilities. The feeling remains, however, that it was mainly due to the official attitude, that above all the country must take advantage of its resources to achieve self sufficiency, that projects with little validity or prospect were pursued too extensively and too long. As so succinctly put elsewhere,[1]

> 'The French failed to implant the process industrially, a fact pregnant with importance for the future of metallurgy'.

It remains to be stated that the production of cementation steel subsequently grew steadily in France. In 1841, some 3631 tons was produced, as against 3159 tons of 'Natural steel'. The details given of this production are :[2]

Pyrenees	2100 tons
Loire	903 tons
Urban Steelworks	352 tons
Others	276 tons
TOTAL	3631 tons

with the following detail for the previous ten years :

1 A. Wertime, The Coming of the Age of Steel (Leiden, 1961), p.205.

2 Le Play, loc.cit. (1843), pp.680-686.

	Cemented Steel	Natural Steel	Cemented Steel Remelted in Crucibles
	tons	tons	tons
1831	2374	2920	156
1832	2281	2700	166
1833	2917	3204	320
1834	2968	3313	262
1835	3254	2902	318
1836	2127	2721	387
1837	2813	3145	463
1838	2974	3428	633
1839	3050	3452	597
1840	3797	3489	845
1841	3631	3159	948

It is also commented that during this period about 1500 tons of crucible steel were imported annually from Britain. Figures available for 1852 indicate that there were then 25 cementation furnaces in France, with a total output of 9808 tons of blister steel, the production of cast steel having risen to 4352 tons.[1]

Official production figures for 1853 indicate that the total steel production in France that year amounted to 15,668 tons, some 11,510 tons being blister steel[2] - only a quarter of the comparable British output at this date.

It is also clear over this period that there was a

1 This information comes from an unidentified 'Treatise on Steel', a damaged partial copy of which exists in the Library of the Brown-Firth Research Laboratories.

2 Ministère de l'Agriculture, du Commerce et des Travaux Publique, Statistique de l'Industrie Minérale, 1853-1859 (Paris 1861), pp.484-499.

growing tendency to depart from the previous policy of insisting on the use of indigenous iron for steelmaking. The Swedish records show that more iron was being imported into France by mid-century.[1] The pleas of Le Play, it would seem, were eventually heeded but the delay in the growth of a viable cementation process in France had the effect of condensing the development stage into a few years and combining this with the search for bulk steel, so that the pattern in France was of a much more intense activity over the forty years from 1840-1880. This period covered the development of the older 'Sheffield Methods' of cementation and crucible steel, the rise of puddled steel, work on the Bessemer process, the Siemens Martin method, largely of French origin, and eventually the adoption of basic Bessemer steel-making, known in France as the Thomas Process.

Crucible steel was obviously appreciated at an early date in France. With the coming of the Revolution, supplies were cut off and the Committee of Public Safety thereupon issued its 'Advice on the Manufacture of Steel'[2] with its

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1 As against some 1640 tons per annum from 1795-99, figures for 1850-54 and 1855-59 are 3647 and 5471 tons respectively. K. G. Hildebrand, Fagerstabrukens Historia, vol.1 (Uppsala, 1957), p.134, and A. Attmann, ibid, vol.II (Uppsala, 1958), pp.24-25. Not all this material was necessarily used for steelmaking, however.

2 Avis aux Ouvriers en Fer sur la Fabrication de l'Acier 'publié par ordre du Comité de Salut Publique'. This was issued about 1793-4 and was based on the work of Vandermonde, Monge and Berthollet. An English translation appeared in Nicholson's Journal, vol.2 (1799). The portion dealing with crucible steel appears on pp.101-102 and p.106, and is reproduced as Appendix EEE.

rousing introduction :

> 'Whilst our brethren are being prodigal with their own blood in the fight against the enemies of liberty, we in the second line must devote all our energies to drawing forth from our own soil all those things of which we have need, so that Europe may learn that France has found within its own body all that is necessary for its courage. We are short of steel, the steel necessary for the arms needed by every citizen to succeed in the fight of liberty against slavery. In the past, England and Germany have supplied most of our needs, but now the despots in England and Germany have cut off all relations with us. Very well, we shall make our own steel.[1]

It seems that as early as 1793 there was an attempt to produce crucible steel in France, since a report of inspection has survived.[1] Whilst it is clear from this document that the main principles were understood, even to discussing crucibles and fluxes, it is not clear that any commercial production took place. It was about this time that Clouet and Chalup[2] carried out experimental work, concluding that good cast steel could be produced by any one of four methods :

a By melting 20 to 30 parts of ductile iron with one part of carbon, with or without the addition of glass as flux, in a Hessian crucible;

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1 Rapport sur la Fabrication d'Acier Fondu du Citoyen le Normand, Reference F^{14} 4485. This document is dated 15th May 1793 and was signed by Hassenfratz. I am grateful to Professor J. R. Harris for providing a copy. A translation, prepared by myself, may be found in Appendix KK.

2 C. J. B. Karsten, translated from German into French and published as Manuel de la Métallurgie du Fer (Metz, 1824), pp.581-582.

b By melting oxide of iron with one and a half to two times the weight of carbon used above;

c By melting one part of oxide of iron with four parts of grey cast iron;

d By melting three parts of pure iron with one part of carbonate of lime and one part of burnt clay derived from crucible fragments.

It seems that the first three methods were repeated by a number of French workers with comparable results. The fourth method, however, was said by Karsten 'not to conform to theory' and he queried whether or not Clouet had used cast iron rather than pure iron and, operating with an imperfectly closed crucible, had oxidised sufficient carbon to turn it into steel;[1] elsewhere, however, it was postulated that silicon induced from the clay had given the hardening characteristics to the metal.[2] Be this as it may, it indicates the urgency with which the nature of crucible steel was being sought, a fact underlined by the offer by 'La Société d'Encouragement pour l'Industrie Nationale' in 1807 of a prize of 4000 francs for

> 'the manufacture on a large scale of cast steel, equal in quality to the most perfect of the foreign manufacturers'

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1 It is significant that elsewhere it is clearly stated that Clouet obtained cast steel by melting cast iron with chalk and crushed crucible; this is then confused by indicating that the mixture could be replaced by the addition of crushed charcoal. This information appears in the footnote to the report by Gillet Laumont. (See Footnote 1, p.562).

2 Karsten, loc.cit., p.582, translator's footnote.

pointing out that

> 'in spite of the knowledge of the theory of the several different processes used for the manufacture of cast steel and the brilliant researches of Clouet, France has not yet obtained from its works all the cast steel necessary for its requirements'.

A report of the examination of the samples submitted survives.[1] The preamble describes the various types of steel available, covering natural steel and cemented steel, and has this to say about cast steel :

> 'Cast steel normally comes from England and exists in two forms in commerce, one known under the name of Marschall steel and the other under the name of Huntzmann steel. Marschall steel appears to have been melted in crucibles with the help of furnaces similar to those in glassworks. It is sold ordinarily in the form of ingots, still carrying the marks of the moulds in which they were cast. Huntzmann steel is forged in perfectly solid bars; it appears to have come from a reverberatory furnace. It is superior in all respects to the Marschall steel. These two varieties of steel are very homogeneous and on quenching in water they take on a great hardness allied to high strength, which makes them suitable for engraving tools and chisels for cutting iron, steel and the hard surface of cast iron without burring, cracking or breaking. They are used for making fine cutlery and will take a superb dark polish, especially that of Huntzmann. These cast steels, which up to now have come to us from England, are of great value to us in the arts, but they are expensive* and may

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1 Gillet Laumont, 'Rapport .... sur l'Acier Fondu', _Journal des Mines_, No.151, July 1809, pp.5-26.

* With regard to cost, it is stated later in the report that the English steel sold at 16 to 18 francs per kg, whilst the inferior French product was offered at 8 to 9 francs. This would indicate that material which sold at £70 to £80 per ton in England fetched up to ten times that amount in France. No wonder Huntsman found this foreign trade to his liking!

> only be forged with particular care. Moreover, they can only with difficulty be forge welded to iron or to other steel'.

The footnote to this paragraph refers back to the evidence quoted by Jars but also comments

> '.... if one can believe reports made by travellers who have recently visited the English steelworks, they are now only using grey cast iron to which they add, as necessary, either lightly cemented steel, to give it hardness, or iron, to give it body'.

There were five entrants: J. C. Fischer, the Swiss steel-maker, provided the finest material but was excluded on the grounds that he was not a French national. Of the other four, only one, that provided by the Poncelet Brothers of Liège, was found to be anywhere near the required standard. This was reported to have been made in crucibles containing from 10 to 18 kg (22 to 40 lb.) of pieces of blister steel, heated in a 'Wind Furnace'.[1] An unspecified flux was used and the melt took from five to six hours, the crucibles normally withstanding three melts. The metal was cast into ingots and forged into bars. These bars, submitted to test, were found to be 'nearly equal' to the foreign steel. It is of interest to note that there is a statement to the effect that, had they used good quality Swedish iron, they would have been able to equal the English steel. As a result they were awarded a gold medal, but the award of the prize was held over to the next general meeting of the Society in 1811, at

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1 This is taken to indicate a furnace with quite adequate draught.

which time there was no further comment. It would seem, therefore, that the restrictions allowing only the use of French iron had again confounded the manufacturers.

With the ending of the Napoleonic Wars, an Englishman working in France changed the scene. James Jackson was a native of Birmingham who had been trained as a steelmaker in Sheffield. He emigrated to France, in 1815, with his four sons, set up a crucible steel works at Trablaine in the Loire Valley and made steel according to Sheffield practice, originally using Swedish iron.[1] In 1816, they produced a total of 100 tons of steel, although they were not satisfied with the clay available for crucibles; their cast steel sold at 4 francs per kg[2] and the blister steel at 1 franc 50 centimes to 2 francs per kg. By 1818, prices had fallen to 3 francs per kg for cast steel and to 1 franc per kg for blister steel; production was now 75 to 100 tons of cast steel and almost 400 tons of blister steel, per annum. There were four cementation furnaces, with a total capacity of 70 tons, and 15 double hole furnaces; the total workforce, including forgemen, was 65; some 14 were English. A suitable

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1 The history of this firm was published privately in 1893 under the title James Jackson et ses Fils. The information set down here, unless specifically referenced, comes from this source.

2 A small amount of English steel which had managed to escape the blockade in 1814 had sold at 12 francs per livre, almost seven times as much.

clay had been found from Ardeche. This was mixed with one fifth of its weight of the same clay, previously calcined, together with 5% of plumbago and 5% coke breeze. The melt weight was 15 kg (33 lb.) for the first melt, 14 kg for the second and 12 kg for the third; although some crucibles had been found capable to giving four, five or even seven melts on occasion, they were normally discarded after three melts to prevent undue loss of metal. In 1818, however, Jackson met trouble. First he received orders that, henceforth, he must use only French iron; then, for some reason, he had to leave Trablaine. By 1820, however, he was operating near St. Étienne, with a 17½ ton cementation furnace, 15 melting holes, a small rolling mill and a file and needle works. Of his 21 workmen only 3 or 4 were English and it is pointed out that they were better treated than the French workforce as they were paid the current Sheffield tariff. It appears that, after some trials, the firm managed to provide steel up to their own standard using iron from the Pyrenees.

After the death of James Jackson in 1829, his sons moved to Assailly and were soon employing 230 men.[1] Their steel had successes at the various Paris Exhibitions, receiving gold medals in both 1834 and 1839. On the latter occasion the jury stated :[2]

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1 W. O. Henderson, Britain and Industrial Europe (Leicester, 1965), p.60.

2 Exposition de Produits de l'Industrie Française en 1839: Rapport du Jury Central, vol.1, pp.387-388.

> 'This steel enjoys the highest commercial reputation. It should not be forgotten it was the Jacksons who first set up in France a plant of any real size for the manufacture of cast steel'.

In 1837 they installed sixteen double melting holes at their works at Berardière, and a year later they had increased the facilities at Assailly to give three 40 ton cementation furnaces and 24 double crucible holes. By 1838, therefore, they had an annual steelmaking capacity of around 1350 tons. It is also of note that whilst the bulk of their common production was from irons from Arriège and the Dauphiné, in 1838 they used, in addition, some 900 tons of Swedish and Russian iron for their 'special steels'. By 1844, they had enlarged their capabilities still further, having 7 cementation furnaces and a total of 52 double melting holes. There is a useful summary of cast steel production in France for this year :[1]

Jackson, Assailly	900 tons
Jacob Holtzer, Firminy	100 tons
MM Holtzer, Cotatay	20 tons
Debrye et Durnaine, St. Étienne	120 tons
Bouvier, Trablaine	60 tons
Verdié Marcelle, Lyons	80 tons
Platé et Roget, St. Étienne	50 tons
Leon Talabot, Albi	100 tons
TOTAL	1430 tons

1 Figures for the total production of crucible steel for the years 1831 to 1841 have been quoted alongside blister steel production earlier in this section. (See p.558).

The import of cast steel the previous year had been 97 tons, 93 tons of which came from England. Jacksons were, therefore, producing almost two thirds of the total French cast steel and, by this date, were importing almost three quarters of the iron they used. There is no doubt that it was the activity of the Jacksons which prompted Le Play to comment :[1]

> '.... the only cast steel made in France which has so far competed successfully with high class British steel is that made in the Loire from Swedish iron. The significant expansion of this industry only dates from 1838'.

In 1850, the Jacksons took over the works at Mottetières and there is an intriguing entry covering the engagement of a Mr. Jessop to direct the melting of the steel; he was an English foreman, skilled in the art. By 1853, they had a total of 15 cementation furnaces with an average capacity of 20 tons and 94 double hole crucible furnaces, producing 4500 tons of blister steel and 2500 tons of cast steel per annum. In 1854, they merged with Petin, Gaudet et Cie, producing 6000 tons of cast steel per annum by 1860. They made quite satisfactory cast steel plates for the French Navy in that year, up to 8 cm thick (3") and 1.5 metres by 0.5 metres (roughly 60" x 20"). These were said to withstand shot better than any plates available; this application was unusual at this date since steel armour was not generally used until about 1880.

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1 Le Play, loc.cit. (1846), p.260.

The situation as regards the French cast steel industry in 1867 is fairly closely known.[1] The Jackson concern had parted company with Petin, Gaudet et Cie by this time and were then at St. Seurin, still using the Sheffield methods to feed 200 crucibles (presumably 100 double hole furnaces) with blister steel, for the eventual manufacture of tools, files and cutlery. Petin, Gaudet et Cie were operating at Assailly and at Loriette, with 15 cementation furnaces of capacities from 15 to 22 tons; their crucible melting was partly coke fired and partly forced draught coal fired; the product of 500 crucibles (containing a total of 12 tons of steel) was available at any one time. The Unieux Works of M. Holtzer, specialising in tool steel, had cementation furnaces and crucible furnaces with up to 200 crucibles, producing 1800 tons per annum. The Firminy Works of Verdié et Cie had previously worked 4 cementation furnaces with 90 coke fired furnaces. Each furnace had four crucibles. Four Siemens type gas fired furnaces, with 20 crucibles each, produced an additional 10 tons of steel in 24 hours using 1500 kg fine coal per ton of steel as against the normal 2750 kg coke. In addition to this economy, the crucibles also lasted six melts in the gas fired furnaces. Nevertheless, in 1866-67, all these had been replaced by four Siemens Open Hearth furnaces. Finally, it was reported that the Société Metallurgique

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1 Jordan, loc.cit., pp.292-298.

de l'Arriège, at Pamiers, exhibited good quality crucible steel, produced from Pyrenees bar iron.

In 1877, there were 101 crucible furnaces in France, producing 7252 tons of ingots. In 1887, there were only 39 furnaces, holding a total of 501 crucibles, but these produced an increased tonnage of 7532 tons; it was pointed out that the old coke fired furnaces had been largely replaced by gas fired Siemens furnaces, with twenty to forty crucibles each, capable of more continuous working.[1] The reports on individual exhibits at the 1889 Exhibition stress the accent on alloy steel; Holtzers were making chromium and 'wolfram' steel; Assailly was producing these, together with nickel steel. Similar ranges came from Firminy, Chatillon Commentry and Rive de Gier, all made by the crucible process.

At the Exhibition of 1900, held in Paris, it becomes clear that much of the alloy steel production had moved to the Open Hearth furnace.[2] Assailly was still producing tool steel from the crucible furnaces. Holtzer et Cie at Unieux exhibited a wide range of crucible steels, derived from charcoal pig iron from Ria in Corsica, partly puddled to steel and remelted direct, partly puddled to iron and

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1 S. Jordan, 'The Iron and Steel Manufacture in France in 1887, as Illustrated by the French Exhibits at Paris', J.I.S.I. (1889, Part II), pp.30-32.

2 H. Bauerman, 'Iron and Steel at the Universal Exhibition, Paris 1900', J.I.S.I. (1900, Part II), pp.160-165.

either cemented and remelted or mixed with the appropriate amount of pig iron in the crucible; in addition, they were making a range of chromium steels with 5% to 30% of the alloy metal, the carbon content throughout held at around 0.4%, with the chromium added as metal, produced by the aluminothermic reduction of chromic oxide. A steelworks near Albi also exhibited cast steel from Pyrenees iron.

Obviously, the overall picture in these later years was much the same as in Britain, with an accent on tool and alloy steels as the main product of the available crucible steel capacity, while bulk supplies for ordinary engineering purposes were obtained from Bessemer or Open Hearth furnaces. The output of crucible steel in France never rose to more than about 40% of the British total. Production figures on a continuous basis are only accessible for the period 1904 to 1926;[1] these show a steady increase from around 8000 tons per annum to a peak of 40,000 tons in 1918, followed by a slump and then partial recovery. Details may be found in Table IX.

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1 Iron and Coal Trades Review, Diamond Jubilee Issue, June 1927, p.215.

IV Germany

Despite the very early work on the cementation process carried out in Germany,[1] there seems to have been little activity in the manufacture of blister steel in that country. Reference to a 'German type' of cementation furnace which was fired with lignite - in contrast to the English use of coal and the Swedish use of wood - appears in 1816,[2] whilst a recently published paper gives no detail whatsoever of any activity on blister steel manufacture in Germany in the first half of the nineteenth century.[3] It is quite clear that the bulk of the steel produced in Germany up to the introduction of the Bessemer and Open Hearth processes in the 1860s was refined direct from pig iron[4], and that this was the original 'German Steel', imported into this country by the cutlers in the seventeenth century[5] and also the basis of the German cutlery industry of Solingen and Remscheid. This is confirmed by a statement that Germany produced some 7000 tons of natural steel, but only 100 tons

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1 These have been described in pp. 79-83; see also Appendix Q.

2 J. G. L. Blumhof, Versuch einer Encyklopaedie der Eisenhuttenkunde (Giessen, 1816), vol.1, pp.282-284.

3 K. Roesch, 'Geschichte des Zementierverfahrens ...', Archiv fur das Eisenhuttenwesen, vol.47 (1976), pp.531-534.

4 J. S. Jeans, Steel, Its History, Manufacture, Properties and Uses (London, 1880), pp.164-168 describes the process.

5 'German Steel' could also refer to steel from Styria and Carinthia, produced by essentially the same process, imported into this country through Germany.

of blister steel, in 1840.[1] The only definite information available on the use of the cementation process in Germany in the nineteenth century, apart from its use in the original experimentation by Friedrich Krupp, to which reference is made below, is that in 1850 there were seven converting furnaces in the Kingdom of Prussia.[2] It appears that Krupp used small quantities of blister steel in 1862 - but only for his 'best brands' - whilst for guns, axles and machined parts the remelting of puddled steel 'with other ingredients' was the normal practice.[3] Certainly the very full description of the works in 1876[4] gives no mention of any cementation furnaces.

Germany was seriously affected by the Continental Blockade during the Napoleonic Wars and the supplies of English crucible steel, much in favour for special uses, were cut off. This stimulated activity, as elsewhere in Europe, and a number of trials were put in hand to determine the secrets of the Huntsman process. Between 1808 and 1812, some progress was made by Andreas Koller at Solingen, Karl and Joshua Busch at Remscheid and Wolfert and Lender at Wald. The last named had to close down 'for

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1 Le Play, loc.cit (1843), p.678.

2 Jeans, loc.cit., p.171.

3 K. Styffe, 'Iakttagelser under et besok i England ar 1862 rorande Jernhanteringen', Jernkontorets Annaler, vol.xvii, (1862), p.334.

4 Jeans, loc.cit., p.180.

lack of means and support'.[1] It seems that in 1812, Friedrich Lohman, who had been experimenting at Bochum since 1809, received an award from 'La Société d'Encouragement pour l'Industrie' for his achievements in crucible steel melting. The Commissioners had examined his steel and had given the opinion that only a little more effort was needed to acquire perfection.[2] He accordingly set up a works at Witten and became the first commercial producer of crucible steel in Germany; his activities, however, were very short lived.

Meanwhile, Friedrich Krupp, in partnership with two brothers von Krechel, was carrying out trials in Essen from 1811 onwards, working on English lines with blister steel as the charge.[3] There was limited success, but more particularly with files made from the blister steel than with cast steel, and the expenses incurred led to the break up of the partnership. In 1815, Krupp entered into partnership with Friedrich Nicolai, who had sole rights for making steel between the Elbe and the Rhine, by a process of his own invention. What his process was is

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1 F. Redlich, History of American Business Leaders (Ann Arbor, 1940), pp.39-40.

2 W. Kossmann, 'Der Beginn der Tiegelstahlherstellung auf dem Europaischer Festland', Stahl und Eisen, vol.82 (1962), pp.218-220.

3 The main part of the information on the early operations of Krupp (and of Mayer, to be discussed below) comes from Redlich, loc.cit., pp.40-51.

not disclosed - he may have been an imposter - but some success was recorded. In 1818, Krupp set up his own factory in Essen.[1] This was to be the nucleus of the later works; originally, he had a melting shop with eight melting holes, each taking one 25 lb. crucible. Two melts were made each day, and ingots of 40 to 45 lb. were occasionally made by 'doubling up'.[2] The crucibles were of Rhenish clay with a considerable addition of graphite. His success may be judged by the official verdict of the 'Verein zur Beforderung des Gewerbfleisses in den Koniglichen Preussichen Staaten',[3] that the product of his factory was found to be

> '.... equal in usefulness and quality to the best English steel and to be in some respects even preferable to it'.

In spite of this propitious inauguration, however, his prosperity quickly declined, due largely to illness and to his overreaching himself financially in the extension of his factory. When he died in 1826 he left a legacy of a largely unoccupied works, and of financial worries, to his son, Alfred Krupp, who was only fourteen at the time.

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1 F. G. C. Muller, Krupp's Steel Works (London, 1898), pp.38-39. This volume is stated on its title page to be an authorised translation; there is a German edition extant, which is presumably the original.

2 This implies the emptying of the contents of one crucible into another when both are ready for teeming and casting the total contents into one mould.

3 The Union for the Encouragement of Industrial Effort in the Prussian States.

Nevertheless, the youth gradually widened his operations, concentrating on quality material. Although for the first ten years the factory is said to have made only enough profit to pay the wages, by 1840 he had more or less achieved the grandiose ambitions of his father and he was clearly the premier steelmaker in Germany. A letter from one of his customers in his first year is enlightening :[1]

> 'I am in receipt of your esteemed letter and am glad to learn that we can once more get steel from you. We found ourselves obliged at the time your father had stopped melting to turn to Herr Marshall of Sheffield for crucible steel; we receive a good kind from him and I will just mention that it has never happened the head of the casting has been drawn out as well and has remained on the bar, which was the case with your last delivery and caused us considerable loss .... We will count on you making sure of bringing your steel to the utmost perfection in manufacture so that we may take all our requirements from you and no longer have to use this foreign Marshall'.

The method used by Krupp must have been very similar to Huntsman's but there has always been some mystery about it.

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1 W. Berdrow, The Letters of Alfred Krupp, 1826-1887 (London, 1930), pp.11-12. The letter was from Herr Kleinstuber, Mechanician at the Berlin Mint, and was dated 24th February 1827. The head of the casting referred to is obviously the ingot top, which should have been broken off before forging. The reputation of Marshall's steel is here again evident.

The official book on the Krupp Works[1] states that

> 'Krupp was the second inventor of cast steel; a mere imitation of the English mode of manufacture, had it been known to him, is shown to be out of the question'.

It is known that he was seeking sources of the good quality Swedish irons in the 1830s[2] but with the firm evidence for the lack of blister steel manufacture in Germany at the time, it is reasonable to assume that 'German Steel' could well have been substituted, particularly in view of the known extensive later use of puddled steel in the Krupp Works.

Some time in the 1840s, Alfred Krupp decided that there were other uses for crucible steel, apart from making small bars for cutlery and edge tools. He commenced the manufacture of hard steel rolls for the mints and the precious metal industries. This required the provision of larger ingots and, in turn, the installation of better forging equipment and, over the next ten to twenty years, led to the evolution of his multiple pouring technique from crucibles to give ever larger and larger ingots, culminating in the provision of steel gun barrels and large engineering forgings.

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1 Muller, loc.cit., p.38.

2 Berdrow, loc.cit., pp.44-45.

It should be pointed out, however, that he had a rival in Germany at this stage. Jacob Mayer, in partnership with Eduard Kuhne, built a cast steel works at Bochum in 1843 and they were to compete in the size of ingot they produced. Mayer made an ingot weighing 1500 lb. in 1849; Krupp went up to 4400 lb. in 1851; Mayer reached 6000 lb. in 1853, and so on.[1] Eventually, Krupp specialised in forgings whilst Mayer, taking other partners in 1854 and founding Bochumer Verein, specialised in castings, having developed a moulding technique suited to the requirements for dealing with crucible steel.[2] The first castings seem to have been steel bells; later the requirements of the expanding railroad industry, both as castings and forgings, took a large part of their output and, here again, they came into competition with Krupp. One of Bochumer Verein's particular specialities was the provision of forged axles, fitted with cast steel wheel centres and rolled seamless tyres, all in crucible steel.

In the Witten area, a number of crucible steel works were established between 1847 and 1862.[3] These included

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1 Krupp subsequently exhibited a 20 tonne ingot in London in 1862 and a 40 tonne ingot, 1.5 metres in diameter, at Paris in 1867 (Jordan, loc.cit., p.308).

2 This was the method taken up by Naylor, Vickers and Company in the late 1850s at their Millsands Works in Sheffield.

3 Kossmann, loc.cit., p.219.

Friedrich Lohmann[1] (1847) who had 116 melting holes by 1866, and Berger and Company (1854) with about 100 melting holes and a number of cementation furnaces by 1869, and there were smaller firms including G. Brinckmann (1855), Flierdt and Company (1857) and Bonninghaus Sohne (1862), each of which had only a few melting holes. A list of other works established to produce crucible steel in Western Germany is as follows :[2]

1855	Peter Harkort, Wetten
1858	J. A. Henkels, Solingen
1864	Richard Lindenberg, Remscheid
1865	R. and H. Boker, Remscheid
1870	Eikenzweig und Schwemann, Hagen
1870	Hagener Guss-stahl Werke
1872	Siegen-Solingen Guss-stahl Aktienverein
1872	Hessenbruch, Remscheid
1874	Eicken, Hagen
1875	Bruninghaus
1887	Eduard Dorrenberg, Runderoth
1895	Rheinmetall, Dusseldorf
1900	Julius Lindenberg, Remscheid
1900	Krefelder Stahlwerk
1907	Karl Kind, Bielstein
1910	Pouplier, Hagen
1926	Fakirstahl Hoffmann, Remscheid

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1 Friedrich Lohmann was the son of J. F. Lohmann referred to above and he presumably opened up his father's works again.

2 This information was kindly provided by Karl Roesch of Remscheid in a private communication. He also informs me that most of the German crucible plants closed down between 1927 and 1935. Julius Lindenberg continued to produce crucible steel until 1953, however. The installations of Julius Lindenberg and at the Pouplier Works were still standing as late as 1972; their subsequent fate was not given, however.

Most of these remain just names. Berger, at Witten, however, are known to have exhibited in Paris in 1867; they had an annual output of 2,500 tons of crucible steel, cast in ingots of up to 8 tons, for ordnance, cutting tools and files. Harkort and Gravemann, of Wetter, were reported as having five cementation furnaces and twelve crucible holes, with an annual output of 625 tons. In addition, a number of the works at Remscheid and Solingen were stated to have taken to the making of crucible steel on a small scale, to support their cutlery trades. One works in Eastern Germany, at Doehlen near Dresden, was founded in 1865 and produced springs, shafts and machine parts from crucible steel made in Siemens type furnaces, fired with lignite.[1]

Without any doubt, however, the premier crucible steel manufacturer was Alfred Krupp. Moreover, having pioneered the production of crucible steel in Germany, he continued its production over the period when other steelmakers had abandoned it for large scale operations. So it is of importance to note the 1898[2] description of operations at Essen, as it indicates the procedure which had been followed for about forty years in what was undoubtedly the largest crucible steelworks in the world. The first part of the account covers the production of the puddled steel,[3]

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1 Jordan, loc.cit., pp.310-311.

2 Muller, loc.cit., pp.29-43.

3 The full description may be consulted in Appendix FFF.

pointing out that its carbon content should be closely controlled between 0.7% and 0.9% and that the raw materials used ensured low sulphur and phosphorus contents. There follows a dissertation on the reasons for the remelting of the steel. It appears that the writer had visited Seebohm and Dieckstahl and Jonas and Colver recently in Sheffield and he commented that they still used the cementation process as a prior stage. He also made the significant statement that

> 'heavy castings and forgings are not now made of the superior crucible steel either in Sheffield or elsewhere in England ....'

but that the process was only used for tool steel 'of the best quality'.

A discussion on the importance of the crucible contains a confession of envy :

> 'Nature has, for the Englishmen, much facilitated the manufacture of cast steel by giving him the clay deposits found near Stourbridge and Stannington. The crucibles made of these clays, in rather a primitive way, with an addition of a very little powdered coke, are ready for use after the comparatively short time of five weeks and will then stand the most severe usage. Other clays, and more especially the German clays, can rarely be used in their natural state but must be made more fireproof and less sensitive to changes of temperature by a considerable addition of certain kinds of graphite'.

The description of the manufacture of crucibles at Essen does, in fact, cover the mixing of several types of clay with a 'considerable amount' of graphite

> '.... worked by men and machinery into a condition of perfect uniformity, then put into a press, from which it issues in the shape of a cylinder, open at either end. This is cut by hand into pieces of equal length, one for every crucible, then the weight of each piece is taken and, if necessary, corrected. Then the pieces are pressed by a wooden rammer into a steel moulding flask, which shapes them on the outside. A conical piston, guided absolutely vertically, is then pressed down in the centre, just deep enough to force the clay to fill the flask to the border which closes it above. After the double flask is opened, the moist crucible (resting on an iron plate, put under it before the pressing process) is lifted into an elevator and transferred to the drying rooms'.

This is an interesting variant on the moulding normally carried out in Sheffield. Here the use of a split flask allowed the production of a crucible with a solid base, rather than with the central hole which then required the use of a stand; there is no evidence of the use of such a stand in the Krupp works.

A further interesting feature is that the crucibles, after charging with metal, had the lid cemented on. This lid had two holes, each about an inch in diameter, one in the centre and the other near the edge :

> '.... the latter serves its purpose when the liquid steel is poured out; the former makes it possible to observe, when desired, the progress of the melting'.

With gas fired furnaces, of course, the complete covering of the charge was not as essential as in coke melting; such an arrangement, obviously, only allowed each crucible to be used for a single melt.

The melting shop itself is likened to an old Roman basilica, with its hall 200 metres long and 80 metres wide, the lofty middle aisle having a central casting channel four metres wide, served by three overhead cranes, whilst down either side were nine Siemens type melting furnaces, each with its own crucible heating oven. The crucibles were charged in a separate annex, the lids cemented on, and they were then transferred by a complicated system of rails and rollers to the door of the heating oven; this seems to imply that the cold crucibles were pre-heated, together with their charges, before being transferred to the melting furnaces. With the furnaces charged and melting proceeding

> 'the whole wide space seems practically deserted .... a few workmen are busy preparing the mould in the middle of the casting ditch for an ingot of fifty tones. The mould is in the shape of a hollow truncated cone; it has thick walls of cast iron and weighs but a little less than the ingot itself. It has been put, wide end downwards, resting on a thick iron plate, into the casting ditch. Now above the mould they cover the pit with iron plates, leaving only two openings. They then set up two long casting troughs leading, with a moderate incline, from both ends of the building to the centre of the pit'.

This again differed from the older Sheffield practice, which used a central tundish set over the mould itself, with all the crucibles required to be poured in a restricted area, with subsequent congestion. The control of the casting stream, however, was better in the Sheffield practice.

The remainder of the description needs to be quoted in full to give an appreciation of the nature of the task and the precision involved; only in Germany could such a procedure have persisted for so long.

> 'When the signal is given for casting to commence, we are confronted by a spectacle which would surprise and fascinate even the blasé audience of a great theatre. On this vast stage swarm hundreds of muffled men, reminding one of ants on a disturbed hill. Among them, as if soaring above the ground, move the glowing crucibles, shedding a red glare on the figures and faces of the men who carry them. And, in contrast, sunbright rays stream from the open furnace doors, over the busy groups below to the girders of the roof above. We soon distinguish that the crowd consists of four currents of men, which, beginning at the farthest furnaces in each corner of the hall, increase as they pass the nearer ones and approach the casting pit. Each crucible is held by double handled tongs and carried by two men. These groups, approaching the casting trough from both sides, pour into it the white glowing, liquid steel through the side hole in the cover of the crucible. After emptying it, which is done in a few seconds, they at once make room for the other groups and, passing down the middle of the aisle, emerge from the crowd, rid themselves of the empty crucible and return to the furnace to repeat the circuit. When such a heavy block is being cast, every group of workmen must carry ten crucibles. At the furnace, we find men busy with the big tongs, putting one crucible after another on the edge. Two men stationed beside them seize the crucible with ordinary hanging tongs and, with one pull, draw it to that corner of the furnace where the foremost group of men stands ready to receive

> it and carry it away. Within half an hour, twelve hundred crucibles, containing fifty tons of steel, are emptied in regular order. Even a layman must understand that such work can only be achieved by means of the utmost skill and a strict discipline enforced by the most intelligent managers who have benefited by many years of practical experience. The whole complicated apparatus works with the precision of a machine. Yet mechanical training has not destroyed the individuality of these men. They move freely and neither their gait nor their attitudes show any military stiffness. No loud commands or expostulations from captain or officers are heard. The little army works almost noiselessly at an eighth wonder of the world. Before the big block solidifies, one or two hours must elapse. It is sure not to contain even the most minute blowhole and to be throughout of the chemical composition which was beforehand determined upon. It is the latter condition especially which renders casting from crucibles superior to any of the more modern and cheaper methods of steel production and this is the reason why, for his cannon, Krupp uses crucible steel exclusively. He has no intention of giving up the practice, although in all other countries open hearth steel is used for these purposes. In manufacturing and in using ingots of crucible steel, weighing up to the astonishing amount of eighty five tons, Krupp's factory stands alone. There are in other parts of the world large steel works, gigantic steam hammers and gun works, but no other puddling works or crucible steel foundry which equals in capacity those of the Essen steel factory'.

It is significant that this description is essentially the same as that given thirty years earlier[1] and that the same procedure was applied to alloy steel ingot-making in the early years of the twentieth century.[2]

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1 C.B.B. in a letter to The Times, 6th September 1866.

2 H. C. Carpenter, 'Alloy Steels: Their Manufacture, Properties and Uses', Jour.Royal Society of Arts (1928), vol.76, p.253.

There are a number of points which require clarification and comment. With a weight of 50 tons coming from 1200 crucibles, the average charge weight must have been almost 100 lb. per crucible. Since this total weight would be derived from eighteen gas fired furnaces, however, each furnace must have accommodated seventy crucibles; as ingots up to 85 tons in weight could be cast, even more crucibles per furnace must have been possible. These gas fired furnaces must have been huge, compared with those in Sheffield, or the American ones, which seem to have held not more than 24 crucibles per chamber. The time taken for the ingot to solidify seems to be a gross underestimate. Such an ingot must have been at least four feet to five feet across the section and with modern casting practice it would be expected to take between 12 and 15 hours for such a mass to solidify; even allowing for the casting speed being slower, and the steel possibly cooler, to move such an ingot after two hours would be extremely damaging to the central structure and likely to lead to unsoundness in the resulting forging. The method of casting employed might well give rise to fewer problems with regard to segregation and variation of analysis, within the body of the ingot, than with modern casting practice; nevertheless, the use of the ingot mould wide-end down, combined with lack of any hot top device, as far as can be seen from any of the evidence in this volume, must have led to some internal unsoundness along the axis of the ingot.

If, of course, the ingot was for the production of a hollow forging, such as a gun tube, this would be of less significance.

It could be stated, however, that the Huntsman process found its fullest development in a form quite different from the intentions of its inventor, in a country which had rapidly developed into one of the major competitors of the old established British steel industry; paradoxically, the Germans retained practices which in Sheffield had become obsolete, largely because of the enormous task of marshalling the necessary labour force, whilst, in Germany, the tacit acceptance of the toil and, presumably, the economic situation, rendered such procedures viable right into the twentieth century. As the anonymous author of a review of the Krupp scene some years earlier stated :[1]

> 'Krupp, being able to draw on a population of drilled soldiers for his crucible men, unconsciously utilised, in casting his enormous ingots, the two years regulation time each of these men had passed in the Prussian army'.

A few production figures for German steel production are available. The output for the years 1837 to 1850 may be found in Table X.[2] The amount of blister steel (which

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1 'Krupp's Steel Works at Essen', The Engineer, 17th August 1866, p.111.

2 Jeans, loc.cit., pp.170-171. Most of this information appears to have been taken from C. Sanderson, Jour. Society of Arts, vol.3 (1854-55), p.457.

was small) appears to be included in the weight of raw steel, from which it is stated both the refined steel and the cast steel were derived. The figures for 1850 include 156 tons of cemented steel from seven furnaces. The cast steel came from 58 melting holes, giving about 15 tons per hole per annum. The raw steel was produced in 143 charcoal hearths (37 tons per hearth), whilst there were 105 furnaces for refining the raw steel; these were part of the old pattern of German steel production. Finally, annual outputs of German crucible steel, and total steel production from 1908 to 1924, are given in Table XI. [1]

V Switzerland

One of the most famous of the early Continental crucible steelmakers was Johann Conrad Fischer. [2] He exhibited his cast steel at the Art and Industry Exhibition in Berne in 1804; this he had made at Muhlenthal, near

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1 Iron and Coal Trades Review, Diamond Jubilee Issue, June 1927, p.209.

2 Most of the detail here is from W. O. Henderson, J. C. Fischer and His Diary of Industrial England (London, 1966). This, in the main, is a translation of Johann Conrad Fischer: Tagebucher (Zurich, 1951). There is some information on his early career in W. Kossmann, 'Der Beginn der Tiegelstahlherstellung auf dem Europaischen Festland', Stahl und Eisen, vol.82 (1962), p.216.

Schaffhausen. It has already been mentioned that Fischer entered some examples of his steel when the 'Société d'Encouragement pour l'Industrie Nationale' offered a prize for high class steel in 1807; whilst disqualifying him as not satisfying the nationality requirements, it was reported that Fischer's steel[1]

> '.... possede réellement les qualités d'un bon acier fondu, sans avoir les defauts'.

Another report states that[2]

> '.... as early as 1809, Mr. Fischer of Schaffhausen had sent to the Society his No.1 steel, said by Ulrich, Schenck and others to be greatly superior to the English No.1 steel. His method differs from that in use in England in so far that he does not, as is generally done in Britain, melt down blister steel, but he produces his steel from bar iron with certain additional substances and he carries out the melt by means of charcoal as a fuel in a cylindrical forced draught furnace containing several crucibles made of a highly refractory clay'.

These, indeed, would seem to have been very advanced techniques for the early nineteenth century. It is clear from later evidence that he subsequently used coke as fuel, but it was then claimed that he was much less extravagant in fuel than the English.[3] Round about 1810 Fischer received

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1 Gillet Laumont, loc.cit. A translation would read 'it has, in truth, the qualities of good cast steel without any defect'.

2 Blumhof, loc.cit., p.507. The translation quoted is by courtesy of Otto Hirston, Esq.

3 R. Wunderlich, Der Beobachter und Berichtstatter in London (Winterthur, 1851).

an invitation from the Czar to settle in Russia, which he declined. During the later years of the Napoleonic Wars, Fischer's steel was of high repute on the Continent and was recommended in preference to the English steel, which was said to have declined in quality. Fischer visited England in 1814; realising the likely competition after the peace, tradition has it that he began to stamp his steel with the mark 'B. Huntsman'. It must be admitted that this seems an unlikely action from one who appears to have been a first class technologist and, indeed, a very estimable character. He seems also to have anticipated Faraday by a year or two, in that he alloyed steel with one third its weight of copper, in 1814, with one fivehundredth part of silver, in 1817, and one seventieth part of chromium in 1824. His silver steel, like Faraday's, was used for making razors and knives. He then produced his 'Meteor Steel', alloyed with nickel. He brought some of this steel with him to England in 1825 in the form of springs, razors and pieces of bar. Ebenezer Rhodes of Sheffield made a pair of razors from his steel and commented very favourably on them. Fischer thereupon made arrangements for Meteor Steel to be made available in England.[1] Fischer's other main claim to

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1 These arrangements were made with Martineau and Smith and the details may be found in British Patent No.5259 (6th October 1825). Details, as per the Abridgements (Specifications relating to the Manufacture of Iron and Steel (Part I, 1620-1866, p.45)) may be consulted in Appendix VV.

fame is that he was the first to make steel castings satisfactorily, as early as 1845. This was only on a small scale and he was soon eclipsed by Jacob Mayer of Bochum and by Naylor, Vickers and Company in Sheffield; he was, nevertheless, the pioneer. Towards the end of his life he produced some alloy steel ball bearings for locomotives. It is tempting to think that these could have been in his chromium steel; it will have been noted that it contained 1.4% chromium and would inevitably have contained a fair amount of carbon - his nickel steel made good razors and thus must have contained at least 1% carbon. If so, it could well be that the 1% carbon, 1½% chromium steel, ostensibly introduced in the early years of the twentieth century and still widely used as a bearing material, was much older in origin and was the first really commercial alloy steel.

Fischer died in 1854. His grandson, Georg Fischer, who had been making steel in Austria, came back to Switzerland and carried on the production at Schaffhausen; He exhibited items of cast steel at Berne in 1857.[1] There is no report of any participation in the 1867 International Exhibition in Paris, however. It seems that the concentration was more on malleable iron castings than on steel by about 1870. The maximum steel

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1 Henderson, loc.cit., p.121.

output recorded was in 1840 when it reached 25 tons per annum; in the years just after the Napoleonic Wars, it had been around 5 tons per annum, whilst in the later years, before the death of Johann Conrad Fischer, it was around 8 tons.[1] This was, therefore, an important, if isolated, phase in the history of crucible steelmaking.

VI Austria

Austria was, of course, the major centre for the production of 'natural steel'; at least up to the introduction of the Bessemer and Open Hearth processes, very little other steel was produced there. In 1842, it produced some 12,600 tons of natural steel and Le Play found no evidence at all for cementation steel manufacture.[2] The main obstacle to the use of the 'English Processes' was a shortage of coal. In 1848, production in Austria was reported as follows :[3]

Raw Steel	4181 tons
Refined Steel	8856 tons
Cemented Steel	125 tons
Crucible Steel	210 tons.

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1 Henderson, loc.cit., p.10.

2 Le Play, loc.cit. (1843), p.692.

3 Sanderson, loc.cit., p.457. Raw steel and refined steel were both forms of natural steel; the crucible steel was produced by remelting refined steel.

It seems, however, that despite the virtual absence of cementation, Austria had one of the earliest crucible steel furnaces on the Continent; it is reported that, in 1796, at Lippitzbach in Lower Carinthia, Max Thaddeus, Graf von Eggar, erected a furnace with a chimney sixty feet tall and with great difficulty and at great expense made satisfactory cast steel from natural steel, produced from the local pig iron. The operation was unusual in that the firing was with hard wood. Max Thaddeus is reputed to have received assistance from two Englishmen skilled in the art, Thomas Lightowler and W. E. Sheffield.[1]

In 1804, Martin Muller, who had visited England, set up a crucible furnace in Vienna; there is said to be an extant drawing which shows it to have had a close resemblance to those illustrated by Andersson and Broling. In 1809, after Napoleon's entry into Vienna, Muller was pressed to sell details of his operations to the French for 200,000 francs, but 'being a true patriot', he refused. The activity was later transferred to St. Aegyd in Lower Austria, around 1825, and steel from there became famous for the manufacture of edge tools, surgical instruments, razors and metal cutting tools. The works was later to become the first in Austria to make high speed steel;

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1 G. Bauhoff, Correspondence, Stahl und Eisen, 14th December 1978, pp.1360-1361.

their 'Velo' brand had a high reputation. It was absorbed by Gebruder Bohler in 1918.[1]

Franz, son of Max Thaddeus, set up a works at Mayerhofl in Central Carinthia in 1818, reputed to have produced cast steel suitable for coining dies and fine edge tools, as good as English steel. This works was producing 50 tons per annum by 1835.

Probably the most important crucible steel works in Austria, however, was that set up by Franz and Rudolf Mayr at Kapfenberg in 1844. Originally they used their own design of forced draught furnace, charcoal fired. With the advent of the Siemens furnace, however, they adopted it with alacrity, using lignite to feed the producers. In 1867, with ten such furnaces, they were producing 1400 tons of crucible steel in ingots up to 2.8 tons in weight, using only three tons of lignite per ton of steel. They had a speciality, termed 'manganstahl', made by melting bar iron with spiegeleisen (the local high manganese pig iron), which was notable for its combination of strength and ductility.[2]

A later description of the works is available.[3]

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1 W. Kossmann, 'Beginn der Tiegelstahlherstellung im Jahre 1804 in Osterreich', Stahl und Eisen, 20th December 1962, pp.1883-1884.

2 Jordan, loc.cit., pp.312-313.

3 A. Ledebur, Stahl und Eisen, 3rd January 1895, pp.1-12.

The charcoal pig iron, from the Eisenerz and Vordernberg ores, was refined to 'raw steel' in the open fire refinery, or was puddled; the former procedure was preferred, since it produced a lower phosphorus content (0.010-0.016% as against 0.018-0.022%) and a better class material when remelted in crucibles. A point was made that the addition of Bessemer or Open Hearth steel to the crucibles had been discontinued, but that from time to time some blister steel, from bar iron produced in the finery, was used, although it tended to be higher in phosphorus than the steel from the same pig iron. The crucibles used were made from Styrian graphite, containing 78% carbon, 13% silica and 6% alumina. For mild tempers (0.3-0.4% carbon) crucibles with 25% graphite were used; otherwise 45% was the rule, the balance being a good refractory clay, all moulding being done in power presses. The furnaces were of the Siemens type, each with room for 18 to 20 crucibles and with its own gas producer and chimney; the latter was 18 inches square internally and 68 feet high. The fuel was lignite slack of poor quality, 2¼ tons being required for each ton of steel melted. The crucibles held about 66 lb. of metal each and were only used once; they were then broken up and some of the uncontaminated material was then blended in with fresh material, to make new ones. Steel analyses quoted as typical were as follows :

	Carbon	Silicon	Manganese	Sulphur	Phosphorus
Metal charged	1.216%	0.257%	0.316%	0.007%	0.013%
Ingot material	1.190%	0.385%	0.234%	0.007%	0.008%

Further modifications to the furnace design took place later, as a description of operations at Kapfenberg in the early years of the twentieth century indicates; it is clear that crucible melting was still a very important part of their operations.[1] The furnaces now each held 40 to 50 crucibles and were erected above ground level to allow handling of the crucibles with tongs and mechanical lifting arrangements. The raw materials used were charcoal pig iron, refined steel, puddled steel and bar iron, together with, at this late stage, the various alloys: tungsten, chromium, molybdenum, vanadium, tantalum and uranium are mentioned. These last two were most unusual as steel-making additions. It is worth quoting that the author of this particular paper was a member of the family which had taken over the works at Kapfenberg some time in the 1880s and, in fact, the firm is still known as Gebruder Bohler. The firm actually set up operations in Sheffield; in 1889 they had an office at 92, Savile Street and they established the Styrian Steel Works at Creswick Walk, in the Pond Street area, in the late 1880s. The manager at this time was Friedrich Korb, who presented a paper in Birmingham which described the manufacture of 'Styrian Steel' (which in this case was the traditional 'natural

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1 R. F. Bohler, 'Tool Steel Making in Styria', School of Mines Quarterly, vol.xxix (1908), pp.329-341. The description of the process is considered worth reporting in extenso and may be found in Appendix GGG.

steel' operation).[1] From existing records at Kapfenberg, however, it seems that ingots and billets of crucible steel were sent to Sheffield,[2] presumably for working down further to bar; the nature of the works in Sheffield is not known, but there was a chimney on the premises.[3]

A further works in Austria, which exhibited at Paris in 1867, was that at Eibiswald, near Graz, producing tools and ordnance in crucible steel.[4] A description of the works ten years later shows the melting to have been in Siemens type furnaces; here, however, they were fired with a mixture of lignite and peat. There were four older furnaces, with nine crucibles each, together with two newer ones, six feet long and three feet broad, each accommodating up to fourteen crucibles. The newer furnaces were more economical in fuel, using only 2½ tons, instead of 3 tons, per ton of steel. The furnaces were lined with quartz bricks but the fire bridges, it should be noted, were built in basic bricks, made from five parts of Leoben magnesite and one part of quicklime - a very early use of basic material, contemporary with the

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1 F. Korb and T. Turner, 'The Manufacture of Styrian Open Hearth Steel', Journal South Staffordshire Institute of Iron and Steel Works Managers (1889-90), pp.3-11.

2 Private communication from Dr. Harald Straube, Gebruder Bohler, Kapfenberg.

3 O.S.1893, Sheffield City Libraries, Sheet 110.

4 Jordan, loc.cit., p.314; Jernkontorets Annaler (1877), pp.71-74.

very early phases of Gilchrist Thomas's work. The crucibles were made from local materials with five parts of graphite to one of fireclay; they only withstood one melt each. Steel was made to various grades from No.1 (1.5-1.8% carbon) to No.7 (0.4-0.7%), the raw materials being their own scrap arisings, blister steel, puddled steel, Vordenberg white cast iron and Austrian spiegeleisen. For No.1 grade, it was noted that 'wolfram' was often added (as with Vickers and Seebohm and Dieckstahl in this country, it will be remembered). The average loss of metal in melting was quoted as 1-2%, as against the more usual 4-5% in Westphalia. It was also noted that the hardness of each melt was checked by a forge test, and the appropriate number stamped on the ingot; no other details of the procedure are given, however. The later history of the works is not known.

Yet another description of crucible steelmaking in Austria has been found; this comes from the very end of the nineteenth century when alloy steel production was not unusual and describes operations at Schloss Schondorf, a site in Upper Austria, well blessed with water power.[1] Here the crucibles were purchased ready made; they were produced from the Passau graphite. The furnaces,

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1 A. Harpf, Osterreichische Zeitschrift fur Berg und Huttenwesen, vol.xlvii (1899), pp.253-258.

unusually in Austria, were coke fired but with forced draught.[1] The crucibles, in batches of seven, were placed on a perforated plate through which the air was blown. The crucibles were only used once. Charges were from 40 to 44 lb; 150 lb. of coke was required for every 100 lb. of molten metal. The charges were made up from local pig irons, all high in manganese (up to 2%) and low in phosphorus (0.019% max.), together with blister steel and local low phosphorus bar iron. Some spiegeleisen, with up to 12% manganese, also produced locally, was used, together with a 10% ferrosilicon - and, again, for very hard steels, a small quantity of ferro-tungsten (30% tungsten) was added. Ferrochromium and ferronickel, both with 30% alloy, were available for special alloy steels and, for deoxidation, aluminium of 98% purity. Clearly, such establishments were not backward in technology.

VII Russia

Little is known, except in general terms, of cementation steel production in Russia. In the early 1840s, some 2640 tons of blister steel was made in the year, two thirds of this in the region of Nijni Novgorod, and the bulk of the remainder in the Urals, of which the works at Nijni Saldinsk

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1 See also p.641 and Appendix JJJ.

received special mention.[1]

Details of two crucible steel works in the late 1870s are available, however.[2] The Aboukoffsky (or Obuchoff) Works was based on materials from the Urals. Good quality charcoal cast iron, low in sulphur and phosphorus, was puddled to bar iron. This material, together with some unconverted cast iron and their own steel scrap, as available - sometimes with the addition of pure magnetic iron ore from the Urals - formed the basis of the crucible charges. The crucibles were made from 20 lb. fireclay, 5 lb. of a further clay, 4 lb. plumbago and 1 lb. charcoal; they held about 75 lb. metal. It seems this works was almost as large as Krupp's since they had recently cast an ingot for the breech block of an 80-ton gun; the ingot was 50 inches in diameter, 130 inches long and weighed almost 50 tons. The ingot took half an hour in casting; although cast in a perfectly cylindrical mould it had no cracks, either longitudinal or transverse. It is particularly stated that the mould was preheated prior to the casting. The most recent addition to plant at the time of this report was a batch of twelve Siemens

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1 Le Play, loc.cit. (1843), pp.672-674.

2 Jeans, loc.cit., pp.255-259.

type furnaces, with a total capacity of 288 crucibles; in addition, there were coke fired furnaces available to provide a further 1000 crucibles of steel at any one time. The ingot, just mentioned, had required the total output of all the furnaces. In addition to guns, these works turned out tyres, wheels, axles and shafts for the Russian railways as well as boiler plates, which were said to have a high reputation. In passing, it should be noted that the famous metallurgist, Tschernoff, who contributed important papers to the Western iron and steel organisations, was employed at these works, which were certainly no mean undertaking.

The Isheff Works at Kama also had crucible melting facilities. There were twenty furnaces, of a local design, but employing gas firing on the Siemens principle. Each furnace took eight 60 lb. crucibles; it seems, however, that only ten of the furnaces were in operation at any one time. The producer was charcoal fired. With lower carbon steel for rifle barrels, only five or six heats were obtained per day, but with the more normal higher carbon materials, seven or even eight heats were common and the furnaces were run continuously for seven to nine days. The crucible charges were a mixture of refined cast iron and wrought iron; spiegeleisen was sometimes substituted for the cast iron. The crucibles were press moulded; the mixture, for a single crucible, was 14 lb. each of clay and crushed potsherds, 6 lb. of Siberian graphite, 1 lb. of English graphite and 4 lb. anthracite; this very heavy crucible was needed to withstand the furnace heat. It was reported that 275 crucibles were used daily; about 30% of these gave out after the first heat and the remainder only served for two heats at most.

Some details of a further works, using a newly installed gas fired furnace, come from a later report.[1] This furnace, at the Poutiloff Works, near St. Petersburg, had three compartments, each for ten crucibles, and a muffle furnace to heat sixty crucibles; it seems to have been on the same plan as those described at a similar late date at the Krupp Works. Each crucible held 72 lb. of metal; the raw materials listed covered Swedish white cast iron, Swedish bar iron, cemented Swedish bar iron, Russian puddled steel and acid and basic open hearth steel, crucible steel scrap, ferromanganese, ferrosilico-manganese and French ferrochromiums (one with 9% carbon and 49% chromium and another with 11% carbon and 60% chromium). The crucibles were again very heavy, weighing about 50-55 lb. each, made from 43% fireclay, 37% burnt clay, 11% old crushed crucible and 9% graphite. The furnace produced 4 to 4½ melts per 24-hour day, casting into 4 inch square ingot moulds. It was normal practice

1 S. Kern, Chemical News, vol.lxv, p.133, p.158 and p.170, abstracted in J.I.S.I. (1892, Part I), pp.427-429.

to add about 1% of the charge as ferroaluminium, prepared by melting 50 lb. of grey cast iron and 22 lb. of 10% silicon ferrosilicon together in a crucible, pouring this when molten into a further crucible containing 12 lb. of aluminium, returning the mixture to the first crucible to mix it and then casting into thin plates, which broke up easily when cold.[1]

Some indication of the level of steel production in Russia at about this time is also available :[2]

	1888 tons	1889 tons	1890 tons
Puddled Steel	2347	3599	423
Blister Steel	1915	1740	1424
Crucible Steel	4195	4877	5333
Bessemer Steel	50389	78424	116439
Open Hearth Steel	159969	166053	245893
TOTAL	218815	254693	369512

VIII United States of America

On 19th October 1655, one John Tucker of Southold on Long Island informed the General Court at Newhaven in Connecticut

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1 Evidence for a similar operation is to be found in a charge book from Cammell, Laird and Co., dating from 1928.

2 A. Keppen, trans. J. M. Crawford, The Industries of Russia: Mining and Metallurgy (St. Petersburg, 1893), p.45. The weights are quoted in poods in the original; they have been converted on the basis of 1 pood = 36.12 lb.

of his[1]

> 'abillitie and intendment to make steele there if he may have some things granted he therein propounds and for that which concernes their jurisdiction they are willing to grant .... as to the takeing clay or wood out of any mans ground they leave it to the towne where he sets it up'.

There was obviously an official interest in establishing such operations since the following May the same court pronounced as follows :[2]

> 'John Tucker of Southold, who is aboute to set upon a way of makeing steele there and had severall priviledges granted to him by this court in October last for his incouragement therein, did now further propound that if his said works should not bee successfull, yet seeing he layes out allmost all his estate upon it, he might notwithstanding be free from rates the said ten yeares before granted which the court considered of and declared that if he doe laye out his estate in such a manner aboute this publique worke and that God shall cross him therein so that he be impoverished thereby they are willing that the small remaining part of his estate shall be free from rates for ten yeares'.

This is the first record of any proposal for steel-making in the American colonies; nothing is known as to whether it was actually set up, what the proposed practice

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1 C. J. Hoadly, Records of the Colony and Plantation of New Haven (Hartford, 1857), vol.2, p.153.

2 Ibid, p.175. A further point worth noting in this volume (p.454) in connection with an iron works is an arrangement whereby one butt of wine and one barrel of liquor drawn shall be free of duty - a very early example of 'allowance', perhaps?

was to be or whether it had any success. The name of the proposer, however, is intriguing, since it may well be remembered that a Charles Tucker, or Tooker, had made steel at Masbrough, by Rotherham, during the Commonwealth - within a year or two of this American proposal - and was involved in a complaint by the 'Cutlers of Halomeshire' in 1662.[1] The possibility of a link between Yorkshire and this American proposal can only be surmised, but is worth noting.

In 1728, however, there is clear evidence of intentions of cementation steelmaking in the proposals put to the Connecticut legislature by Samuel Higley and Joseph Davey[2] since it was given in evidence that Higley

> '.... had, with great paines and cost, found out and obtained a curious art by which to convert, change or transmute common iron into good steel sufficient for any use and was the first that ever performed such an operation in America'.

They requested the exclusive right of steelmaking in Connecticut for 25 years; they were granted a patent for ten years

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1 Rhys Jenkins, 'Notes on the Early History of Steelmaking', Trans. Newcomen Society, vol.iii (1922-23), p.24.

2 W. F. Durfee, 'Development of American Industries since Columbus, Popular Science Monthly, vol.xxxix (1892), pp.729-730.

'.... provided the patentees improve the art to any good and reasonable perfection within two years after the date of this act'.

That they had previously produced a reasonable product was attested by two smiths, Timothy Phelps and John Drake, on 7th May 1728 and their testimony dispels any lingering doubts that it was the cementation process which was involved :[1]

'Samuel Higley .... came to the shop of us being blacksmiths and desired of us to let him have a pound or two of iron .... which we according to his desire let him have, shapeing severall pieces according to his order. He desired that we would take notice of them so that we might know them again for, said he, I am going to make steel of this iron and I shall in a few days bring them for you to try for steel. Accordingly he brought the same pieces which we let him have and we proved them and found them good steel, which was the first steel that was ever made in this country'.

In spite of this, however, it seems doubtful whether Higley and Davey complied with the terms of the patent since, before its expiry in 1740, the sole rights of steelmaking in Connecticut were granted for 15 years

'.... upon the condition that they should in the space of two years make half a ton of steel ....'

to Fitch, Walker and Wyllis.[2] In turn, they failed to

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1 A communication from C. J. Hoadly, Librarian of the Connecticut State Library, quoted by J. M. Swank, History of the Manufacture of Iron in All Ages, 2nd ed. (Philadelphia, 1892), p.379.

2 Ibid, p.380.

comply with the terms laid down. In 1744, however, Aaron Eliot and Ichabod Miller certified that they had produced more than this amount at their furnace at Symsbury. By 1750, Eliot had a furnace at Killingworth and he seems to have continued in the trade for many years, since he was granted loans from the public treasury to further his steelmaking activities between 1772 and 1775 so as to

> '.... save large sums of money within this colony which is annually paid to New York for the steel manufactured in this colony ....'

since he had been obliged to buy his iron from New York on credit and pay for the same in his steel at a fixed price of £56 per ton, whilst it would fetch from £75 to £80 on the open market.[1] This same Aaron would also seem to have been the Colonel Eliot of Connecticut

> '.... a gentleman of ability in the steel way for many years, whose furnace was complete and large ....'

who was engaged to make trials by the Rev. Daniel Little.[2] Little himself had been granted[3]

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1 Durfee, loc.cit., p.730.

2 Rev. Daniel Little, 'Observations Upon the Art of Making Steel', Memorials of the American Academy of Arts and Sciences, vol.1 (1785), pp.525-528. The text is reproduced in full in Appendix HHH.

3 W. B. Weeden, Economic and Social History of New England, quoted by Durfee, loc.cit., p.731.

'.... £450 by the legislature of Massachusetts in 1778 to aid in the erection at Wells a building 35 feet by 25 feet to be used in the manufacturing of steel'.

It is separately reported that there were five steelmaking furnaces in the colonies in 1750, two in Pennsylvania (both in Philadelphia) and one each in Massachusetts, Connecticut and New Jersey.[1] The operations in Philadelphia were those of William Branson, who stated that[2]

'.... the sort he made, which was blistered steel, ten tons would be ten years in selling'

and of Stephen Paschal, whose furnace was built in 1747 and seems to have had a continued existence, since it was operated in 1787 by Nancarrow and Matlock at the time of a visit by General Washington, who pronounced it the best and largest in America.[3] Since the British Act of 1750 prohibited the erection of further steelmaking furnaces in the colony, these five blister steel furnaces, if so they all were, represented the sum total of steelmaking activity at the time of the Revolution. It seems, however, that one way round the Act was to refine pig iron direct to steel and in New Jersey both Peter Hasenclever and William Hawkhurst were separately following this route by 1776. Hawkhurst, indeed, was

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1 It appears that all colonial governors were called upon to verify the state of the 'Iron Trade' in that year.

2 Swank, <u>loc.cit.</u>, pp.381-382.

3 Durfee, <u>loc.cit.</u>, p.731.

advertising for men[1]

> '.... to make pig metal into steel in the German way ....'

having two furnaces operating and six nearing completion. The same process seems to have been used during the Revolution in Rhode Island, where in 1777 they[2]

> '.... gave £60 per gross ton for good German steel made within the state'.

At the same time, the furnace at Trenton for the making of blister steel was reconstructed on a larger scale than formerly and the works at Andover, in New Jersey, recently seized from loyalists, were put to work again in 1777.[3]

In 1787, Jonathon Leonard erected at Easton, Massachusetts, a steel furnace capable of making three tons of blister steel at a batch. This continued in use until 1808, when it is reported that commercial requirements dictated the building of a ten ton furnace.[4]

Meanwhile, Alexander Hamilton, Secretary to the U.S. Treasury, reported on 5th December 1791 that[5]

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1 New York Gazette and Weekly Mercury, 8th April 1776.

2 Weeden, loc.cit.

3 Pennsylvania Gazette, 4th June 1777.

4 S. L. Goodale, Chronology of Iron and Steel (Pittsburgh, 1920), entry for 1787.

5 American State Papers, Documents Legislative and Executive of the Congress of the United States, vol.v, p.124.

'.... steel is a branch (of the iron trade) which has already made a considerable progress and it is ascertained that some new enterprises on a more extensive scale have latterly been set on foot. The facility of carrying it to an extent which will supply all internal demands and furnish a considerable surplus for exportation cannot be doubted. The duty upon the importation of this article, which is at present seventy five cents per hundredweight, may, it is conceived, be safely and advantageously extended to one hundred cents. It is desirable, by decisive arrangements, to second the efforts which we are making in so very valuable a branch'.

In the same year it was also stated that[1]

'.... about one half of the steel consumed in the United States is home made and new furnaces are building at the moment. The works being few and the importations ascertained, this fact is known to be accurate'.

The relatively small scale of this industry, based on either the cementation furnace or the German refining methods, is confirmed by a report from 1810 that the total steel production in the country was 917 tons, from ten furnaces.[2] Five of these were in Pennsylvania, producing some 531 tons between them, with one furnace each in Massachusetts, Rhode Island, New Jersey, Virginia and Carolina.

It was at this time that two important events took place. The first was the commencement of steelmaking at Pittsburgh, later to become the 'Sheffield of America', by

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1 Swank, loc.cit., pp.382-383, quoting Tench Coxe in reply to Lord Sheffield's 'Observations on the Commerce of the United States'.

2 Swank, loc.cit., p.383.

the erection of a cementation furnace there in 1810. The other was the first recorded attempt, albeit an unsuccessful one, to produce crucible steel in America. This was in New York in 1812 by John Parkins and his son, both steelmakers from England, who were subsequently employed at Valley Forge in Pennsylvania, about 1818, for the production of cast steel for saws; this was another short lived and, presumably, unsuccessful enterprise.[1]

There is an extensive report on the art of steelmaking in America in 1831.[2] This shows a complete reliance on cementation steel, with fourteen furnaces capable of an annual production of 1600 tons of steel. This implies an average furnace capacity of around eight tons. Of these furnaces, three were in New York, another three in Philadelphia, two each in Pittsburgh and New Jersey and one each in Baltimore, York, Troy and Boston. The report states

> 'Steel imported here from England amounts to so considerable a quantity that the competition for ascendency in our market must rest between that nation and this. We already supply ourselves, to her exclusion, with common steel.

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1 Swank, loc.cit., pp.383-384.

2 B. F. French, History of the Rise and Progress of the Iron Trade of the United States (New York, 1858), pp.49-54. These pages carry a reprint of the Report presented by B. B. Howell to a Convention of the Friends of Domestic Industry, held in New York in November 1831.

> The iron of this country, when properly made, had been shown to be equal in quality to the Russian and Swedish iron used in England for conversion into steel and, being so converted, is employed in making large and rough implements of manufacture and agriculture. It is used for the fabrication of plough-shares; it is worked up by shovel makers, scythe makers and cross-cut and mill saw makers use more than any other manufacturers. One factory of this kind in Philadelphia requires a ton and a half of steel per diem, every working day of the year .... The English, however, continue to supply us with the superior qualities'.

There follows a description of these superior qualities, covering blister steel made from the Dannemora irons, shear steel from such blister steel and, above all, cast steel. In the ensuing discussion there can be detected something of the same attitude which, in its pursuit of self-sufficiency, so long hindered the French steel industry :

> 'It is, however, a cause for congratulation here that iron of similar or equal quality to that which has thrown all the advantages of manufacturing the best articles of cutlery into British hands has recently, by improved processes, been made from the ore of Juniata, and both sides of the line between New York and Connecticut, the latter denominated the Ancrum, the Livingstone and the Salisbury ore. Steel is now made in Pittsburgh and may be made in New York and Connecticut, bearing a fair comparison with the best Hoop L or Dannemora steel that comes from England. No difference is observed where trials have been made without disclosing the origin of either to the judges'.

It is then pointed out that, with such steel and the possibility of importing the skill and experience, bearing in mind the fact that English steelworkers

> '.... wanting employment or adequate recompense for labor at home, continually seek these amongst us and it is believed that these may be afforded to such an extent as to yield them support commensurate with their industry and that ingenious men, who under other circumstances might have been compelled to pursuits not congenial with their education, or to be dependants on public bounty, will become useful citizens ....'

there should be no real problems in providing the necessary requirements in shear steel, thus avoiding the necessity for dependence on Britain, in this respect. As far as cast steel was concerned, however, it is made quite clear that none was produced in the United States at this date, all attempts to produce it so far having failed on account of :

> '1. The want of best quality blister steel (of which it only can be made) at a reasonable price.
>
> 2. The want, or expense, of crucibles in proper quality wherein the blister steel is to be melted'.

The hope is expressed that, the first problem having been solved by the use of the Juniata iron, the second difficulty may also have been overcome since

> '.... the explorations of the present year have disclosed the existence of clay analogous to that of Stourbridge, which is considered the

> best in the world for crucibles. Centre, Clearfield and Lycoming counties in Pennsylvania have yielded large specimens of clay that satisfy geologists, mineralogists and chemists of the identity of its properties with those of Stourbridge .... The great impediment to the making of steel has not arisen from any mystery in the art but the want of strength in crucibles'.

The hopes for the future of the American steel industry, not in the event to be realised immediately, but to be achieved gradually over the next half century, were expressed in the final paragraph of the report :

> 'Capital, enterprise and perseverance will be engaged to bring this desirable material, so indispensable to the finer arts of cutlery and machinery, into market, if protection be continued to the efforts which our citizens are willing to make. If these views are correct, we have steel for agricultural purposes in the greatest abundance; we have steel for nicer purposes and we have cast steel for the most refined articles of manufacture among ourselves. But that is not all - we may export our steel to Russia, Prussia and France in competition with England herself and thus justify the further importation of foreign commodities which we can have the means of paying for. The subject of steel becomes more interesting as our investigation of it advances; but it is believed that the facts and inferences now set forth will suffice to continue the protection already granted and to procure time for more extensive practical development which, if realised, will add to the means of domestic employment and beneficial intercourse with foreign nations'.

There were, it is quite clear, many attempts to achieve this situation and much expense and effort was put into the establishment of crucible steelmaking in America. Yet in

1847, the thirteen steelworks of Pennsylvania, now the heartland of the young American steel industry, between them only produced 6078 tons; moreover, only 44 tons of this was crucible steel.[1] Ten years later it was stated that American cast steel was hardly known in the markets.[2] Yet there is a story to tell, whose theme runs as follows :[3]

> 'The production of a quality of steel that should triumphantly compete with the English article is a success story belonging solely to Pittsburgh; for although the manufacture of steel had been attempted by persons in various sections of the United States, and some of the lower grades made, yet we are unable to find record of any establishment outside Pittsburgh that succeeded in producing a reliable tool steel of a quality equal to the English article. The enterprise was about abandoned in this country when the success of the Pittsburgh manufacturers revived its spirit; since when several establishments have been put into operation at different points, but leaving Pittsburgh as the only great steel producing market of America, where are made all qualities, from the lowest grade of blister up to the finer qualities of tool, sabre and cutlery steel'.

With regard to crucible steel, there seems to have been a first, but unsuccessful, attempt in Pittsburgh around 1830. Simeon Broadmeadow, an Englishman, apparently made perfectly satisfactory blister steel from local charcoal iron, but the

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1 This figure comes from the report of the Philadelphia Convention of Ironmasters in 1847, quoted by J. M. Swank, loc.cit., p.385, and also by W. F. Durfee, loc.cit., p.735.

2 Swank, loc.cit., p.385, quoting from Appleton's Cyclopaedia of 1860.

3 G. H. Thurston, Pittsburgh and Allegheny in the Centennial Year (Pittsburgh, 1876), p.191.

quality of the cast steel made from it was poor.[1,2]

> 'The failure was no doubt attributable to the want of proper material and this cause was, for a long time, the obstacle in the production of the higher grades of steel with all who attempted its manufacture until it was fast becoming a received opinion that it could not be made from the native irons of America. Years of experience and perseverance have, however, established the contrary fact and, as before stated, steel equal to the best imported article has been, and is daily, produced from native irons in the steelworks of Pittsburgh'.

Despite this statement, however, it seems that the first attempt to produce cast steel, in America, which can claim to have been reasonably successful did not take place in Pittsburgh but in Cincinnati, where two Englishmen , the brothers William and John Hill Garrard, set up a works in 1832. This included a ten ton cementation furnace and two crucible holes holding two pots each; the product was intended for making saws and files.[3] In the August they made their first cast steel and, by November, had produced satisfactory cross

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1 Swank, loc.cit., p.389.

2 The quotation which follows is again from Thurston, loc.cit., p.191.

3 H. Gilmer, 'Birth of the American Crucible Steel Industry', Western Pennsylvania Historical Magazine, vol.xxxvi (1953), pp.23-24. I am indebted to Professor Landes for a reprint of this useful article which, although drawing extensively on Swank, does contain other material of interest.

cut saws and mill saws.[1]

> 'I made my own blister steel .... The first crucibles I experimented with were German plumbago pots, but they were a failure, as they spoiled the steel by giving out too much gross carbon. I then went to Western Virginia, near New Cumberland, and found a clay that very much resembled English Stourbridge clay and by putting into the pots made from it about the same proportion of burnt clay material they stood about as well as the Stourbridge pots and answered my purpose very well'.

With regard to the material used by the Garrard Brothers, for the charges to the crucibles, there is other evidence:[2]

> 'For best cast steel he used Swedes iron. For steel used for saws, springs, etc., he used Tennessee charcoal iron. For best cast steel he also used Missouri charcoal iron. In addition to saws and springs, he made steel for chopping axes, files and tools in general. The material used was all very high priced, so that the owners were obliged to sell their spring steel at from 10 to 15 cents per pound and their best cast steel at from 18 to 25 cents'.

The business failed in 1837, not from any technical problems but because the Garrards could not match the credit terms of the English suppliers or overcome the prejudice against American steel and the established preference for the British import. They sold primarily to customers who wanted good tools in a hurry and had the cash available. As Dr. Garrard reported :[3]

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1 Swank, loc.cit., p.386, quoting a communication he had received from Dr. William Garrard.

2 Swank, loc.cit., p.386, quoting a private communication he had received from James E. Emerson, a personal friend of Dr. Garrard.

3 Communication from Dr. Garrard (Swank, loc.cit., p.386).

> 'I sold my steel and manufactured articles principally to manufacturers. There were some wholesale houses that bought of me, but they were importing houses and when the Sheffield manufacturers found I was making as good steel and manufactured saws and files as good as they did, they gave our merchants such an extended term of credit that they bought as little as possible from me'.

With regard to the termination of the business,[1]

> 'The enterprise was started during Jackson's first term of office and about that time the law was passed for a gradual reduction of duties on all imports for a decade. .... foreign importation increased, to pay for which the country was drained of money. Manufactures were closed, culminating in the great panic of 1837, at which time the enterprise of our venerable friend went down in the general wreck that engulfed the infant manufactures in their cradles all over the country'.

The Cincinnati cementation furnace remained in operation until about 1844 but there was no more crucible steel made there, or indeed anywhere in America other than in Pittsburgh, for many years.

Among the early Pittsburgh pioneers were G. and J. H. Schoenberger, who had been producing blister steel since 1833; they set up six crucible melting holes in 1840, bringing over a certain Edward Dunn[2] from England, to be in charge of the first operations of their type in

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1 Communication from J. E. Emerson (Swank, loc.cit., p.387).

2 Jeans, loc.cit., p.140. According to Thurston, loc.cit., p.192, operations commenced in 1841 under Patrick and James Dunn.

the town. The works was quickly extended, having 18 to 20 melting holes within a couple of years.[1] Nevertheless, the firm was short lived, again largely on account of the prejudice against American steel.[2] The steel seems to have been produced from blister bar made from the Juniata iron; it seems that they had been so confident that no domestic iron could in any respect equal the Juniata material that, when they failed to produce from it a steel fully equal to the Sheffield product, they found steelmaking too much of a problem.[3]

During the period 1845 to 1850, two more Pittsburgh firms, Jones and Quigg, of the Pittsburgh Steelworks, and Coleman, Hailman and Company, both produced cast steel, but only of lower grade material, mainly for agricultural purposes.

The firm of McKelvie and Blair commenced making files in 1850, and in 1852 began making crucible steel to satisfy their needs. They may be rightly considered the first successful large scale producers of this material in Pittsburgh. That their success was short lived was not

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1 Thurston, loc.cit., p.192.

2 Jeans, loc.cit., p.140, reports that, in order to overcome the prejudice, the American manufacturers resorted to the ruse of throwing salt water over their billets and slabs and then allowing them to weather for some weeks, so as to give a similar appearance to the English material after the Atlantic sea crossing.

3 Gilmer, loc.cit., pp.24-25.

indicative of faulty technique :[1]

> 'McKelvie and Blair at first made their pots out of Derby and Stannington clay imported from England. The brilliant success of Joseph Dixon of Jersey City, New Jersey, in perfecting the manufacture of plumbago crucibles, for which the crucible steel interest in the United States owes him a monument, gave to that firm and to the Jersey City Steelworks a very valuable lift. With these crucibles and with Adirondack blooms Mr. Thompson made some excellent steel. Along in 1853 and 1854 McKelvie and Blair made steel from the Adirondack blooms which were used in the nail factory of G. and J. H. Schoenberger. It may be added, also, that the knives and dies of nail cutting machines afford an admirable test of the endurance in tool steel. The American steel from the American iron was fully up to the English steel in every particular. It was not possible for McKelvie and Blair to obtain the Adirondack blooms in any quantity and they had no other resource than the Champlain and Missouri blooms, all of which produced red short steel. This, notwithstanding the drawbacks, found a ready market so extensive that the firm sent to Sheffield and brought out several skilled workmen and the business of manufacturing handsomely finished bars, plates and sheets was fairly inaugurated. The drawbacks of pioneer systems, however, chief among which was the abominable English system, imported with the skilled labour, of 'working to fool the master', were too much for the financial strength of the firm and in 1854 they were forced to drop the enterprise'.

This, however, was not to be the end of operations on the site, since the works were started up again, as will be related below, by Hussey, Wells and Company in 1859. It will be noticed that, once more, one of the main reasons for failure was the strong prejudice in favour of

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1 Gilmer, loc.cit., pp.24-25, quoting a communication from Thomas S. Blair.

English steel; it is stated elsewhere[1] that the lack of protection which might have been afforded the growing steel industry by the imposition of a tariff on imports was a serious error on the part of the government.

The reference to the development of suitable crucibles by Joseph Dixon merits further comment.[2] As early as 1827 he had experimented with Ceylon graphite as an ingredient in metallurgical crucibles and appears to have demonstrated that they were capable of withstanding steelmaking temperatures; his own attempts at steelmaking are said to have failed 'as a matter of chemistry'. The use of his crucibles was, quite clearly, a major contribution to the success of the New England copper and brass industry. It appears that Dixon moved to New Jersey and became associated with the Adirondack Iron and Steel Company there in 1848. Their earlier attempts to produce cast steel had failed, largely on account of the poor quality clay crucibles. With Dixon's plumbago crucibles and the pure Adirondack iron, however, they produced in 1849 what was described as the most superior of all American cast steel. Inevitably, however, the economic pressures were too great and this company also failed in 1853.

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1 In a document of unspecified origin, dealing with the Park Works in Pittsburgh, probably dated 1877, provided by the Crucible Steel Company of America. (See Appendix III).

2 This information is mainly from Gilmer, <u>loc.cit.</u>, pp.21-22 and 25-26.

In 1849, Singer, Nimick and Company set up the manufacture of blister steel in Pittsburgh; they called their establishment the Sheffield Steel Works. Whether this was an act of faith or merely an attempt to procure business on the strength of the name is a debatable point; the works was, however, destined to have an honourable future. From 1849 to 1853, it concentrated on the production of blister steel, spring steel (rolled or forged down blister steel) and German steel (or shear steel); it then turned to the manufacture of crucible steel and gradually established a reputation for quality. Isaac Jones, the successor to Jones and Quigg, also commenced the manufacture of crucible steel on his own account in 1855. His works also survived and grew, later becoming the firm of Anderson and Woods.[1] The two major Pittsburgh works which finally made the break-through, and eventually challenged British competition, however, were established a few years later. These were Hussey, Wells and Company, set up in 1859, and the Black Diamond Works of Park Brothers, in 1862.

The timing of these enterprises should be noted since two contributory factors were involved. In the first place, Joseph Dixon, from about 1858, was producing a much improved crucible, blending graphite

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1 This information and much of the story up to 1865 is derived from Gilmer, loc.cit., pp.26-32.

with the Klingenberg clay imported from Germany; of this work, Dr. Hussey was at least aware, if not actually party to it. Secondly, the Republican Tariff Act of 1861, known as the Morrill Tariff, gave the protection to home produced manufactures, which James Park and other local industrialists had been advocating for some time. This latter factor, combined with raids on shipping during the Civil War, which considerably curtailed imports, gave the young industry the opportunity it had needed.

Dr. Curtis G. Hussey[1] had been involved in the copper and brass industry in the Pittsburgh area and had set on a young student, Calvin Wells, to assist in his other business of pork packing. Wells was subsequently sent to New Jersey to investigate the activities of Joseph Dixon and the Adirondack steel melting operations, in the early 1850s. In 1859, Hussey purchased the old McKelvie and Blair premises in Pittsburgh, erected new buildings and, in 1860, had succeeded in making cast steel direct from iron bars, without the need for making blister steel. The method used is not known but seems to have been successful since there are no cementation chimneys visible in a lithograph of the extensive works of fifteen years later.[2]

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1 It is of interest to note that Hussey was a Quaker, so continuing the tradition of the non-conformist pioneer.

2 Thurston, loc.cit., illustration facing p.198.

James Park, unlike Hussey and Wells, was a Pittsburgher born and bred. Originally a storekeeper supplying metal goods, who then became involved in cotton spinning, he was well aware of the deficiencies of the steel which was available for machinery parts. He later founded the Lake Superior Copper Works for the production of copper sheathing for ships. This brought him into contact with the other metal consuming industries and with plant for handling metals. He then moved into steel production and set up the Black Diamond Works, which made its first melt of crucible steel on 1st May 1862. Originally, production was aimed at about 5 tons per day 'with fifty hands'. The methods used were the traditional ones from Sheffield and the melting was, in the first instance, under the supervision of Sheffield workmen imported for the purpose. The iron was first converted into blister bar and costs were higher than at Hussey, Wells and Company; Park, however, set out to diversify more, producing softer steel as well as tool steel, and his enterprise thrived. Black Diamond steel was exhibited at Paris in 1867 and was greeted with considerable approval.[1] The works were gradually extended and in

1 Jordan, loc.cit., p.316. Park Brothers were said to have drawn attention by the beauty of their products.

1877 occupied seven acres[1] and included six thirty ton cementation furnaces, a row of 72 coke fired Huntsman type furnaces and three Siemens gas fired units, producing over 35 tons of crucible steel per day.

Outside Pittsburgh, it should be noted that the old Adirondack Iron and Steel Company was purchased in 1863 by Gregory and Company and produced best quality crucible steel for many years, only being abandoned in 1886.[2] Meanwhile, in Pittsburgh, two more important establishments were founded during the Civil War: La Belle Steelworks in 1863 - this still being in operation in 1940[3] - and the Crescent Steelworks in 1865. Both had the usual combination of cementation and crucible furnaces.[4]

An interesting operation, alongside all this crucible

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1 This description is contained in a document of unknown origin, kindly provided by the Crucible Steel Company of America. It provides a lithograph view of the works and a full description of operations; the text can be consulted in Appendix III. Since it refers to only sixteen years having elapsed since the necessary protective tariff gave the fostering of the new industry, the date can be placed around 1877-78.

2 Swank, loc.cit., p.391.

3 A magnificent set of photographs taken at La Belle Steelworks was published forty years ago - Metal Progress, May 1940, pp.543-551. These gave me my first impressions of the crucible melting process.

4 Anon, A History of Allegheny County (Pittsburgh, 1876), p.111.

steel activity, was that at the Albany Works at Troy :[1]

> 'The firm of Corning, Winslow and Company is now extensively engaged in the manufacture of puddled steel, which they commenced soon after the art of effecting it was made known in Germany about the year 1852. Few men in this country, if any, have devoted more attention to this subject than Mr. Winslow. Their puddled or semi-steel is capable of bearing a tensile strain ranging from 90,000 to 108,000 pounds to the square inch (40-48 tons per square inch) and is beyond doubt equal in every respect to any made in Europe. This material is now largely made into locomotive tires, boiler plates and other forms where great strength and density are required. It is further manufactured by cementation and put into spring steel for carriages and rail car purposes. Corning, Winslow and Company, we believe, are at present the only makers of semi-steel in the United States'.

Light rifled guns were made from their 'semi-steel' in 1861 and 1862.[2] It is reported elsewhere that puddled steel was also produced by James Horner and Company at Pompton, New Jersey. Moreover, some 1185 tons of puddled steel was produced in America in 1870, but the process was obsolete by 1880.[3]

The growth of steelmaking in Pennsylvania is reported as follows :[4]

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1 J. L. Bishop, <u>A History of American Manufactures</u> (Philadelphia, 1868), vol.3, p.251.

2 <u>Scientific American</u>, 29th June 1861, p.405; 7th September 1861, p.149; 12th April 1862, p.227.

3 Durfee, <u>loc.cit.</u>, p.740.

4 J. B. Pearse, <u>A Concise History of Iron Manufacture .... in Pennsylvania</u> (New York, 1876), pp.256-257.

1847	13 steelworks, blister and cast	6078 tons total (only 44 tons cast steel).
1856	6 steelworks operating with a total capacity of 8500 tons.	
1864	14 steelworks, one quarter cast, three quarters blister	9771 tons produced.
1873	16 cast steel works	33151 tons produced.

Up to 1867, all crucible steel had been produced in the conventional Huntsman type furnaces, although it is possible that some were fuelled with anthracite rather than coke.[1] In November 1867, however, Anderson and Woods, the successors of Isaac Jones, obtained a licence for the installation of the Siemens regenerative furnace. A 24-crucible gas fired furnace of this type was erected in their works in the spring of 1868.[2] The widespread adoption of this type of furnace can be appreciated from Table XII, which gives the situation in Pittsburgh in 1876.[3] The advantages of such furnaces become clearer when it is appreciated that 'gob' (or coal slack) could be had in Pittsburgh for only 45 cents per ton, as compared with $2.40 for large coal or $3.50 for coke.[4]

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1 F. Overman, The Manufacture of Iron, 3rd ed. (New York, 1854), p.477.

2 Durfee, loc.cit., p.736.

3 Thurston, loc.cit., p.196.

4 Jeans, loc.cit., p.141.

By 1876 there were 60 steel works in the United States.[1] 38 made crucible steel, the remainder producing puddled steel, Open Hearth steel or steel from steel scrap. Seven of the 38 crucible steel works also produced blister steel and German steel. The output of these types of steel totalled 49,641 tons in 1874, 61,058 tons in 1875 and 71,478 tons in 1876, this latter total including 39,382 tons of crucible steel. An independent source gives the production the previous year as 61,000 tons, produced in 44 works; the output of crucible steel is quoted as 40,000 tons.[2]

It is worth commenting at this stage that competition from Sheffield was still a force to be reckoned with in America, and in 1876 Sanderson Brothers of Sheffield took the step of entering America as a producer, setting up the Sanderson Halcomb Works at Syracuse. Their example was followed by Firths, who established Firth Sterling, and by Jessops, well before 1900. The Sanderson Halcomb Works, which was eventually absorbed into the Crucible Steel Company in 1900, subsequently made history as the

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1 These figures exclude those producing Bessemer steel. Jeans, loc.cit., pp.143-144.

2 Clark, loc.cit., p.249.

first firm in America to instal an electric arc furnace in 1906.[1]

As in England, the stage was set by this time for the supersession of the older methods by the Bessemer and Open Hearth processes, with the crucible steel makers taking on the role of specialist producers, alloy steel being destined to play a major role. By 1920, for instance, high carbon-chromium steel for bearings, 13% manganese steel, stainless steel and high speed steel were regular production items for the crucible furnaces; moreover, clay lined plumbago crucibles were specially prepared for the melting of the low carbon stainless steels, whilst for the manganese steel the ferromanganese was specially melted in a short crucible, to be added at the end of the melt of the 13% manganese steel, to prevent undue attack on the main crucible.[2]

The organisation of the crucible melting firms in

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1 This furnace shell is still preserved as an outside exhibit at the works at Syracuse and was inspected by the author while in America some years ago.

An amusing result of the importation of a number of English workmen to America was reported in Engineering and Mining Journal, 10th July 1880. A number of Sheffield cutlers, taken over by one Sheffield firm to make razors, had insisted on taking over with them tanks full of Sheffield water for the quenching of the blanks. The same article also states that they would only work with English steel and if the material was suspected to be American they would be sure to spoil it.

2 This information comes from an anonymous article entitled A Brief History of Park Works, kindly provided by the Crucible Steel Company of America.

America underwent a major rationalisation in 1900. At this time, the Park Steel Company, the successor to Park Brothers, was reputed to be the largest single producer of special steel in the world. They approached the other American crucible steelmakers and the result was the amalgamation of sixteen companies, on 16th July 1900, to form the Crucible Steel Company of America, with William G. Park as Chairman and James H. Park as a director, both of them sons of the founder of the Black Diamond Works.

Crucible steel production in America reached its peak in 1907 with another, virtually similar figure, in 1916. The process lingered on tenuously for almost a further thirty years. Significantly, however, it showed a resurgence in 1941-42, just as in England. The full details of production from 1863 to 1946 can be found in Table XIII.[1]

The foregoing history has been largely derived from American sources, all of which lay stress on the triumph of the local steelmaker over the English opposition, and they also pay particular attention to the satisfaction gained by using domestically produced iron rather than imported material. With the details of Swedish iron

1 Iron Age, Centennial Issue, June 1955, Supplement M4, which in turn draws on the official statistics of the American Iron and Steel Institute.

imports into the United States available from Swedish sources, however, this does not quite ring true.[1] One American source, however, tends to confirm this :[2]

> 'Between 1820 and 1860 we imported large quantities of manufactured iron, mainly in the form of hammered or rolled bars .... almost entirely from Sweden and Norway, although Russia occasionally provided part of our foreign supply'.

The impartial observer must come to the conclusion that the importance placed on domestic self sufficiency, coupled with the effectiveness and experience of the suppliers of the competing imported material, set back the progress of the domestic steel industry for a number of years, and the drawing of a parallel with the situation in France is inescapable. On the other hand, it must be admitted that, once the know-how became disseminated - be it to a considerable degree from the Sheffield area by importing those skilled in the art - the progress of the American industry was extremely impressive.

It is worth while, therefore, to include some fairly detailed information on American practice, from a late

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1 Details of the American production and import of iron are presented in Figure D of Appendix YY.

2 V. S. Clark, History of Manufactures in the United States (Washington, 1916), vol.1, pp.252-253.

stage in the history of the crucible process, dealing with the production of high speed steel.[1] The preamble to this discussion sets the stage in 1930 :

> 'The preparation of high speed steel is carried out most simply by melting the proper ingredients together in a crucible. This was the earliest method of manufacture and was for many years the most widely used. It is still not uncommon to find it regarded as the best, or at least the safest for uniformity of quality. In the United States at present a very much larger amount of high speed steel is made in the electric furnace than is made in the crucible but this has become true only in the last decade .... In England a large portion of the tonnage of high speed steel is still made in the crucible although the larger ingots for large size bars are for the most part made in the electric furnace'.

The process subsequently described is that of melting in graphite crucibles in gas fired furnaces. The crucibles, in general holding 100 lb. of metal, are indicated as being fatter and squatter in proportions compared with the standard English 60 lb. crucible. It is interesting to note that it is still stated that

> 'In English practice advantage is taken of the fact that highly useful refractory clays are readily available. English steelmakers have made their own pots of these clays adding just enough coke - about 5 per cent - to impart the necessary strength at high temperatures. The pots are generally made by hand at the plant where they are to be used .... being relatively fragile they could not safely be transported .... More recently graphite pots are gaining favour in England'.

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1 M. A. Grossmann and E. C. Bain, High Speed Steel (New York, 1931), pp.1-10.

The build up of the charge is discussed and two examples are quoted, as detailed in Table XIV. It is made quite clear that, whilst the control of the alloy additions is relatively simple, that of the carbon content is not so, the chief difficulty being the variable absorption of graphite from the crucible. The factors affecting this are listed as follows :

1 Time of melting
2 Temperature of melting
3 Presence of flux
4 Composition of the metal
5 Time of adding manganese and silicon.

The higher the melting temperature and the longer the time of holding, the greater will be the carbon absorption from the pot, and thus the higher will be the carbon content of the steel; this seems a very reasonable argument, in the light of other evidence. The American practice obviously differed from the English in the addition of brick dust and sand, as can be seen in the Table. The ostensible function of such an addition was to absorb the oxides of iron, from the surface of the iron or the scrap, to prevent them from attacking the clay bond of the crucible and thus releasing further graphite into the melt. The influence of the composition of the metal charged relates to the observed fact, in this American practice, that a high chromium melt appeared to produce a higher carbon absorption; it was argued that the high affinity of chromium for carbon could abstract graphite from the pot wall, the resulting carbide of chromium then dissolving in the liquid metal.

There were clearly two different schools of thought in American practice, with regard to the addition of silicon and manganese. One method was to add them both with the charge; the other to add them when the pots were withdrawn. It should be noticed that this last procedure could only be applied when the contents of several pots were mixed together in a ladle prior to casting. This procedure, let it be made clear, was a much more usual practice in America, at this time, than casting from single crucibles, as in Sheffield. The first method, therefore, was much more in line with Sheffield practice, but in a graphite crucible the manganese and silicon would tend to react with the slag and, on balance, give rise to a higher carbon increment; when it came to 'killing' or a holding period, the carbon absorption would rise steeply. The second method would give better control on carbon increment and could be run hotter with less risk of crucible erosion; it was, therefore, more popular with melters and more widely used. There was, nevertheless, a feeling that the original method gave the better steel, due, it was thought, to the lower dissolved gas content in the cooler steel. If the steel were to be poured into a ladle, however, it needed to be hotter, due simply to the cooling action of the ladle, preheated though it was. This procedure of itself, with the added opportunity of fluxing further refractory material in the ladle, would tend towards a less 'clean' steel in the final ingot. That the ladle had its advantages, particularly in making for a more uniform analysis, cannot be doubted; this is underlined by some figures quoted for the carbon content of a series of nine ingots from one melting campaign, with uniform charges to all pots, which were then 'doubled up' - that is, the contents of two pots combined and poured together into one mould. The carbon content showed wide variation and it has to be commented that, had each pot been poured to a single ingot, the variations would have been even wider :

Ingot No.	Carbon Content
1	0.88%
2	0.74%
3	0.57%
4	0.77%
5	0.74%
6	0.85%
7	0.78%
8	0.88%
9	0.92%

The variations from one part of the furnace to another, as regards temperature, were commented upon, as was the better control of carbon content available in England from the use of clay pots; it was noted that this allowed the direct pouring of ingots with variations from ingot to ingot of only a few hundredths of a per cent of carbon.

The problem of carbon clearly had received considerable attention in America. A typical melt of high speed steel was sampled at various times with the following results :

Total carbon charged (in muck bar and ferroalloys)	0.34%
Carbon in the melt at the 'mushy stage' (near melted)	0.58%
Carbon in sample when just melted	0.57%
Carbon in sample 25 minutes later	0.61%
Carbon in sample a further 25 minutes later	0.71%

This last sample, after a 50 minutes 'killing', just before pouring, represents a pick up of 0.37% carbon, absorbed from the crucible; the amount of this pick-up seems to have been used as a gauge of the melter's skill. It was, nevertheless, an accepted fact that new crucibles gave a higher pick-up; in one particular trial, with twelve identical charges in a variety of crucibles, as regards their previous usage, the following figures were obtained :

New Pots	0.45% pick-up
'First Heaters' (used once previously)	0.40%
'Second Heaters' (used twice)	0.39%
'Third Heaters' (used three times)	0.39%

The other comment made is to the effect that, although the chemical analysis may be the same, the quality of steel made with a virgin charge (muck bar and ferroalloys) is superior to that from a charge with from 25% to 35% scrap; nevertheless, it was rare that scrap was not incorporated in the charge since economics dictated that the discards arising during manufacture should be absorbed during subsequent production, to cut down on the new alloy requirement.

It is worth noting that nowhere is there any suggestion that Swedish iron should be incorporated. The Sheffield steelmakers had reverted to the use of Swedish iron for their high speed charges, when it became more readily available again after the end of the War. In the twentieth century, however, the Americans were being consistent in their self sufficiency. Twenty five years earlier, in presenting a paper on high speed tool steels, an English author had stipulated that Swedish iron was essential for quality.[1] One American authority replied that his company believed that they made as good a product as the next steelworks, although they did not use Swedish stock of any kind, adding the further comment :[2]

> '.... the traditions of the past should not be accepted as conclusive if there is any way of testing the matter'.

A representative of the Crucible Steel Company present went further and stated categorically that Swedish iron was not necessary :[3]

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1 J. M. Gledhill, 'The Development and Use of High Speed Steel', J.I.S.I. (1904, Part II), pp.127-167.

2 H. H. Campbell, in discussion, ibid, p.169.

3 J. A. Matthews, in discussion, ibid, p.170.

'We get equally good results using Swedish or any of a great number of domestic irons whose analyses are as good or better than Swedish iron. Sulphur at 0.007% and phosphorus below 0.01% are not unusual in American irons'.

So the argument went on until the final days of the crucible process.

It is also of interest to note that the American steelmakers seem to have adopted slightly different terminology - as they adopted slightly different technology - in their day to day operations.[1]

In the cementation process, the trial bars, usually referred to in England as 'tap bars', were known in America as 'spies' or 'regulator pieces'. The 'sap', or soft centre of a lightly cemented blister bar, has a dull appearance; in America it was said to be 'killed' or 'dead'; the bright part of the fracture looked 'raw' or was said to 'stare', whilst the over-cemented bars referred to in Sheffield as showing a 'facetted' fracture were 'flaked'.

In crucible melting, the furnace cellar seems to have been known as the 'cave'. The Americans appear to have used the Continental practice of filling a warmed crucible

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1 H. P. Tiemann, Iron and Steel: A Pocket Encyclopaedia (New York, 1933). The information quoted comes from the entries 'Cementation', pp.80-82, and 'Crucible Steel', pp.132-138.

(bearing in mind that it was always a plumbago one) and charging this into a pre-heating zone (bearing in mind again that their later furnaces were invariably gas or oil fired). They therefore employed a 'pot packer' to charge the crucible and a 'setter in' to transfer the charged crucible to the furnace. The steel in the crucible after the killing fire in Sheffield was obviously 'killed'; in America it was simply 'dead'. During the killing period bubbles of gas formed in the crucible; as the process continued, these became fewer and larger, due to the growing viscosity of the thin layer of slag present. The Americans therefore looked for the formation of 'cat's eyes', large infrequent bubbles, as an indication the steel was virtually 'dead'. During teeming the Sheffielders used a 'mop' - a bar with a blob of solidified slag on the end - to hold back the small amount of slag; the Americans used a 'flux-stick'. Probably the most intriguing term in America was reserved for the store-room for raw materials, particularly the alloy additions: this was the 'medicine room' - presumably the 'physic' was kept here also!

IX Japan

Crucible steel manufacture was introduced to Japan from the west in 1882, when a batch of coke fired furnaces was built at the Naval Ordnance Depot in Tokyo. Local iron was used and crucibles were imported from Morgan Crucible in England. Steel for saws and tools was followed by the manufacture of guns and bullets. Gas fired furnaces were introduced after a short time and, using local clay and graphite, satisfactory crucibles were produced. Within a few years special steels and larger ingots were being made.

Further crucible furnace installations were made at the Osaka Arsenal in 1889 (together with Open Hearth furnaces, which were also erected at Tokyo in 1895). In 1904 the Yawata Steel Works installed gas fired crucible furnaces, eventually reaching an output of 150 tons per month, making tool steel, including high speed steel, as well as gun barrels. Yonago Steel Works also installed crucible furnaces for alloy steel production in 1905. The first electric arc furnace was erected in 1908, but the Japan Special Steel Company chose to instal two large Siemens type crucible furnaces in 1914.

The manufacture of high speed steel, tool steel and, later, stainless steel had become firmly established using the crucible process, although the manufacture of lower carbon grades proved difficult, due to the universal use of graphite crucibles. Trials with clay lined graphite crucibles were only partially successful in combating the problem of carbon pick-up and the more serious consideration of the electric arc process and the eventual decline of the crucible process were inevitable. In Japan, however, there was still a useful role for the crucible process until about 1948.[1] Some impression of the scale of operations in Japan may be obtained from the figures quoted in Table XV.

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1 The whole of this information is derived from Yoshio Ishihara, partly from 'Progress of Special Steelmaking in Japan', Symposium on Production of Alloy Steels (Jamshedpur, 1958), pp.172-175, and partly from a private communication.

It is worth commenting that, according to Professor T. Ko, the introduction of western steelmaking methods into China late in the nineteenth century was initially concerned only with the Open Hearth process. By 1914, however, there were some small crucible steel installations in China, mainly in the region of Shanghai; no details are available.

POSTSCRIPT

Since the completion of the text, further information relevant to the later operations of the crucible process at the Cyclops Works of Cammell, Laird and Company in Sheffield has become available.[1] This is considered of sufficient interest to be included and it has, accordingly, been set down in Appendix JJJ. At the end of 1923 it was decided to replace most of the coke fired Huntsman type furnaces with Morgan forced draught type units. These were found to give a higher output - up to four heats in a twelve hour day - at a lower coke consumption per ton of steel. It was necessary, however, to use a plumbago type crucible, since the clay crucibles would not stand the heat. This led to some problems in carbon pickup in the metal; certain qualities of steel were therefore melted in clay lined plumbago crucibles, particularly the various grades of stainless and heat resisting steels which were beginning to be produced via the crucible process at this date. For some steels, however, even this was not suitable and a number of special melts, including the 36% nickel low expansion steel which was, it would seem, required in some quantity, were produced in the old type of clay pots using the few remaining Huntsman type furnaces.

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1 This information has kindly been provided by T. R. Middleton, Esq., who was in charge of the crucible melting operations at Cammell Laird from 1922 to 1929 when they were closed down. He has very kindly sorted out a number of documents and charge books and allowed me to study these privately; in addition he has given me his personal reminiscences of this very interesting period when the crucible furnaces were still the main source of high quality tool steel but were also being used to produce experimental materials, many of which have survived to the present day.