and lends itself readily to very considerable fluctuations in the daily tonnage produced. The side-blown equipment being cheaper than the bottom-blown is less affected by shut downs.

Oil or coal burning crucible furnaces can be operated intermittently as easily as continuously, and their installation cost is so low that shut downs are relatively inexpensive.

Electric furnaces can be operated intermittently, but had far better be kept constantly hot, since the power consumed in heating them up is considerable, and the wear and tear on the furnace due to heating and cooling is severe. That shut downs of large (and hence costly) electric furnaces greatly increase the cost of metal, goes without saying.

SUMMARY

Process	Quality	Flexibility	Suitability for small work	Cost of steel	Tonnage	Cost of installation	Cost of installation per ton
	1 best	1 most flexible	1 most suitable	1 lowest	1 highest	1 lowest	1 lowest
Crucible	2	1	1	6	5	1	6
Electric	1	2	2	5	4	3	5
Acid open-hearth	3	4	5	2	1	5	3
Basic open-hearth	4	4	6	1	1	5	4
Side blown Bessemer	6	3	3	4	3	2	2
Bottom blown Bessemer	5	3	4	3	2	4	1

Note.—Electric furnace refining basic open-hearth steel stands between No. 3 and No. 4 in cost of steel.

Note.—Gas-fired crucible furnace stands between 3 and 4 in cost of installation.

Note.—Electric furnace refining hot metal stands No. 1 in cost of installation per ton.

CHAPTER III

THE CRUCIBLE PROCESS

The crucible process is the oldest of the steel-making methods now extensively used, and like practically all our modern processes is "indirect"; that is, steel is produced from some other product derived from the iron ore.

In very early times, both steel and iron were produced directly from the ore in open forges. These consisted essentially of an open basin or hearth in which very pure iron ore was heated in contact with a large excess of charcoal, the fires being blown with bellows or other primitive means of producing blast. Part of the ore was reduced by solid carbon, according to the usual formula,

$$FeO+C=Fe+CO,$$

while a considerable amount of the FeO combined with the silica, lime, etc., of the gangue of the ore to form a fluid or pasty slag. The metal obtained from these forges was in the form of a coagulated mass of small particles, much like a puddled "ball," and was hammered to squeeze out the slag contained in the interstices, cut into pieces, heated to welding and rehammered, until a fairly pure and uniform bar was obtained. If the metal absorbed much carbon from the charcoal a steel of varying degree of hardness was obtained. As a rule, however, soft, carbonless iron was the product desired, and in order to convert this into steel it was heated in a bed of charcoal out of contact with the air until it was cemented or case hardened to the center.

Later, the soft iron used for cementation was produced from the new product, pig or cast iron, by melting a bar of pig iron with a charcoal fire in an open hearth, and allowing the slowly melting iron to trickle down through the air blast used. By the oxidizing action of the blast, the carbon, silicon, manganese, sulphur and phosphorus of the pig were eliminated and nearly pure iron was obtained in a sponge of coagulated particles and slag, which was worked up as before. By this method also either iron or steel could be obtained, but iron was the usual product. This is the principle of the Walloon hearth and other like methods, by which Swedish charcoal iron is still made to-day.

The practice of cementation (or total case hardening, as it might be called), gradually developed as time went on, and as used in England to-day has made great strides in the furnaces employed, though in principle it is still the process of Tubal Cain. In the modern cementation furnaces, bars of soft iron are packed in long cast-iron boxes, each bar well bedded in pulverized charcoal, and two or more of the boxes are heated to full red heat in a conical topped, coal-fired furnace. After full heat is reached, it is maintained from 7 to 11 days, the progress of the absorption of carbon being watched by occasionally taking out a test bar through holes in the ends of the pots and when the desired degree of carburization has been reached the furnace is allowed to cool slowly. These "blister bars," as they are called, are broken when cool, the "temper" (or carbon content) estimated by the appearance of the fracture, and are then hammered out into longer bars, a product known as "spring steel." Cut, piled, heated, welded, and hammered out into bars once or twice, the product is "single-shear" or "double-shear" steel. These steels are still extensively used in Sheffield for cutlery and many tools in which a steel edge is welded to an iron back.

About 1740, Huntsman, a watchmaker of Sheffield, dissatisfied with the far from uniform steel of his day, hit on the scheme of melting blister bar in clay pots or crucibles, and made the first crucible steel produced in England. Naturally this steel was a great improvement on "double-shear" and at once largely displaced all other steels for high-grade requirements. With characteristic conservatism, Sheffield steel makers adhere to-day to Huntsman's methods, and for high-grade tool steels melt only blister bar of uniform temper, made from Swedish charcoal iron. Puddled iron, they maintain, will not make as fine a steel as the charcoal product, and is used in Sheffield only for poorer grades of steel.

It is hard to see the special virtue of spending two weeks soaking carbon into the iron in the solid state and then melting the product, when the two operations can be carried out simultaneously in a few hours. American steel makers pack soft iron and charcoal (or washed metal), into pots, melt down the iron, which absorbs the charcoal or the carbon of the washed metal, and obtain a steel of the desired "temper" in four or five hours. Our precedent for this practice is found in the ancient steel-making industry of India, Arabia, and other parts of the East, where for untold centuries steel has been made by remelting in clay pots with wood or charcoal, iron produced directly from the ore in crude hearths similar to those already described. The pots are luted tightly, packed in a charcoal fire, and the contents melted as in American practice, the soft iron absorbing carbon from the wood or charcoal and becoming hard steel. By this process were produced the long famous blades of the Orient, of which we have all heard perhaps as much as we can stand, and which must be our justification for claiming that as good steel can be made by cementing and melting in one step as by the slow and costly methods so largely followed in Sheffield.

Puddled iron, invented by Cort about 1784, is the raw material chiefly used to-day in America for fine tool steel and when carefully made, with low sulphur and phosphorus we claim that it will produce a tool steel as good as any. Indeed, except that it is made with soft coal as fuel instead of charcoal, and out of a fluid bath not in contact with the fuel, instead of out of a succession of drops of fluid iron running through the air blast, it is hard to see wherein the metallurgical features of the process differ from those of the Walloon hearth. The claim is made that we do not so thoroughly work the slag out of our puddled bar as is the case in charcoal iron practice, but since in remelting in pots practically all slag floats out of the puddled iron, it is not easy to see the advantage of working the slag out of the solid iron by rolling and hammering. To suppose that the mechanical working imparts a "quality" or "body" to the iron that persists in the molten steel is too great a strain on our credulity to warrant serious consideration.

The crucible process has been used for so many years that tradition and superstition have gathered upon it like moss on an old wall, and this discussion is purposely made explicit and rather long in order to set forth the matter in what appears to the author its true light. Purchasers of castings so frequently state that after years of unsatisfactory experience with makers using other processes, they at last adopted crucible steel, and never had any more trouble, that it is as well to state clearly and at once that their relief from their troubles is chiefly due to the ease with which small and intricate castings of crucible steel are poured solid and free from blow holes, cracks and flaws, and to the pains that makers specializing in small castings habitually take with their product, and not to mysterious, cure-all virtues of the process itself.

Let us then consider for a moment the reasons for the excellence of crucible steel, and the practice generally followed for the production of crucible steel castings, in order to see to what extent great excellence of steel is usually striven for and actually obtained. To begin with, as crucible steel making is a pure melting process, no removal of phosphorus and sulphur is possible, and the content of these elements even increases slightly, because the loss of metallic iron reduces the total weight of the molten steel as compared to that of the iron charged; and in the case of sulphur, because some sulphur is absorbed from the coke, coal or gas used in melting. For this reason low sulphur and phosphorus have to be obtained by the use of very pure raw material, either "low phosphorus" charcoal or puddled iron, or basic open-hearth scrap. If acid open-hearth or Bessemer scrap is used, the phosphorus and sulphur will be relatively high, and quite often by the indiscriminate use of plate-steel punchings whose origin is not known or whose analysis is not obtained, crucible steel is produced much higher in these objectionable elements than good practice should allow.

Excellence of the steel is further due to the fact that by melting in a closed pot with a cover either luted on, or soon sealed fast by the "running" of the pot and cover with the heat, the steel is protected from the oxidizing gases of the furnace, so that it does not oxidize and absorb its own oxides, nor absorb great quantities of harmful gases. There is, to be sure, air in the pot at the beginning, but the oxygen of this air is soon exhausted in the oxidation of charcoal in the pot, or of carbon, silicon and manganese of the iron, so that a neutral atmosphere is soon attained. This is, of course, lost when the cover is slid off to examine the steel, but the advantage from this source is well known and beyond dispute. Further, silicon, either absorbed from the clay of the pot by the reduction of silica, (SiO_2), to silicon, by the carbon of the steel, or added as ferrosilicon, reduces much of the oxides present in the metal, and renders it much "quieter" when poured, either by freeing the steel from gas, or by increasing the capacity of the steel to hold the gas in solution. Thus in crucible melting, open-hearth scrap is considerably improved in quality, and if hard tool steel be the product, it is better than open-hearth steel as such.

Tool steel practice, however, which tries the steel very high, has demonstrated to the satisfaction of the steel makers and steel users that crucible steel made of open-hearth scrap, however low in phosphorus, sulphur and manganese, is not as good as crucible steel made from puddled iron. The English makers and users, as already noted, carry this even further and will use only charcoal iron for the finest steels, and cement it before melting at that. As this superiority of tool steel made from wrought iron seems to be established beyond dispute, there must be some inherent excellence of wrought iron, not shown by the analysis for silicon, manganese, sulphur and phosphorus, which renders it superior as a raw material for crucible steel to open-hearth scrap of equivalent or superior analysis.

This excellence must be due to the method of manufacturing wrought iron, and to get an idea of what causes it, we must compare carefully the methods used for producing puddled iron and basic open-hearth steel of equal purity, as shown by the usual analysis.

In both the puddling furnace and the basic open-hearth steel furnace, a bath of molten iron high in carbon, silicon, manganese, sulphur and phosphorus is subjected to the action of iron ore in a highly basic slag, and of an oxidizing flame, in order to oxidize their impurities, and remove them either as gases (CO), or by sending them into the slag as oxides (SiO_2, MnO, etc.). The final product of both is nearly pure iron; but the temperature of the puddling furnace is so low that the metallic iron becomes solid as fast as it forms, a molecule or a tiny particle at a time, and by the gradual coagulation of these small masses a sponge of pasty iron particles is formed, whose interstices are filled with liquid slag; whereas the open-hearth furnace is maintained at so high a temperature near the end of the process that the metal is kept molten, poured into a ladle and thence into large ingots, where it cools relatively rapidly. The puddling process corresponds to the early stages of the basic open-hearth process, and it is owing to the lower temperatures that the slag, which is not very high in lime (CaO), and is very high in iron oxide (FeO), is able to retain phosphorus as phosphate and largely eliminate this impurity. In basic open-hearth practice, though considerable phosphorus is held in the slag when the metal is first melted, much of this phosphorus is reduced again from the phosphate by the action of iron and carbon at high temperature, and a very limey slag has to be made after the richly ferrous slag has performed its function of removing carbon, silicon and manganese, in order to hold phosphorus in solution and thus eliminate it from the steel by oxidation.

As in both processes the metal is exposed to highly oxidizing slag and gases, the difference must be chiefly in the lower temperature and the relatively slower and particle by particle solidification of the metal in the puddling furnace. It has always seemed probable that at the lower temperatures of the puddling furnace the metal absorbs less oxide and gases, especially since the very pure iron formed near the end of the process at once freezes, instead of being long exposed to oxidizing conditions when it has no silicon and manganese to protect it from oxidation, as in the case of the open-hearth furnace; and that the particle by particle solidification of wrought iron gives an opportunity for throwing dissolved gases and oxides out of solution that is largely denied to open-hearth steel frozen rapidly in large masses. To be sure, ferrosilicon and ferromanganese are added to remove a great part of the oxides, in open-hearth practice; yet they are often added in the ladle, and that their cleansing effect is far from complete is too well known to require argument.

From this discussion it is plain that crucible steel as such, is not necessarily a product of the highest excellence. If made of very pure materials properly melted, it is better than any other steel except the electric steel of to-day. If made of basic open-hearth scrap, even of very low phosphorus and sulphur, it is not a great deal better as steel than the scrap of which it was made. And if scrap is used indiscriminately without analysis, a very poor product may be the result. We have already set forth briefly in the introductory chapter our reasons for assigning superior quality to electric steel, and will dwell upon the matter more at length in the chapters devoted to the electric process. It is sufficient to point out here that the very moderate quality of crucible steel as generally made for castings is not at all as high as that of fine brands of tool steel, and cannot conceivably be called equal to the quality of well made electric furnace steel. It is just as well to state again, however, that for the great bulk of castings made by the crucible process, it is poor policy to use expensive puddled iron or charcoal iron in order to give the steel the fine quality of best tool steel. No casting is ever called upon to show the excellence of steel needed to make a tool stand up to long-continued metal cutting, and castings properly made of crucible steel, using basic open-hearth steel scrap as raw material, will exhibit physical properties that show that they are amply able to endure the stresses to which they are to be subjected in service. More especially is this the case when the castings are annealed by simply a short heating and slow cooling to relieve strains and somewhat improve the grain. We make our tools of the very finest steel in order that they may take the best possible temper when carefully hardened and temper drawn. If we similarly heat treat our castings so as to give them the very highest strength and greatest toughness they can be made to possess, and find we need still finer steel than we can obtain from remelted scrap, we naturally will turn to high-grade irons as raw materials. But if we only roughly anneal our castings, and do not nearly bring out the best that is in them, there is no need of using such very costly raw materials.

Castings are generally desired of mild steel, .25 per cent. carbon being the average content for most purposes. Many makers of crucible steel castings have difficuly in producing mild steels, as will be explained presently when we consider the control of analysis, and produce a great deal of steel that for most uses is too hard and brittle for the best results. This is a disadvantage of the process that frequently gives the steel maker trouble.

The real advantages that make the crucible process well suited to the manufacture of castings, especially light and intricate castings, and alloy steels of certain kinds, have already been touched upon in the introductory chapter. They are:

First, the low cost of installation of the process for starting a small shop.

Second, the high temperature of the steel, and the fact that it can be kept hot in the furnace until needed. Moreover, when pouring small castings, the steel can be poured directly from the hot pot, which being a poor conductor of heat with a small exposed surface of metal keeps the steel hot and fluid very well indeed. This is the more true because the steel is not chilled by pouring in a stream into the pot, as in the case of filling small "shank" ladles from a larger ladle. In addition to this, the steel is very free from gas, is smooth running and if well "killed" or purposely made high in silicon, feeds down exceedingly well in the risers, "sets" quietly in the moulds, and produces very sound, clean castings. This advantage, coupled with cheapness of installation, are the two chief reasons for the use of the process, in spite of the high cost of the steel produced, for the manufacture of small, intricate castings.

An advantage of less weight in the majority of cases is the flexibility of the process, as already explained in the introductory chapter. Naturally, as each pot is a separate lot of steel, many different kinds of steel can be made at one heat in quantities to suit the requirements of the shop. The only limits to this are the number of pots melted, and the ability of the melter to attend to a number of different kinds of steel at once. We shall see further on that the difficulties of producing at will just the analysis desired, limit the possible number of sorts of steel that a melter can be expected to produce sucessfully at one heat. There is not a very great demand moreover, for castings of special analysis, at least of steels that can be economically produced in crucibles, so that this flexibility is not often taken advantage of.

THE FURNACES

The furnaces used are the old-fashioned anthracite coal or coke hole, the oil-fired furnace, and the regenerative gas furnace of the pull-out (American), and side drawing (Krupp), types.

The coke hole is very little used in America, though coke is often used with anthracite in our practice in this country. The general style of hole used here for anthracite and in Sheffield for coke is about the same, and can be briefly described as a set of oblong melting holes lined with clay brick, with a flue at the back into which a small flue leads from each melting hole. One stack provides draught for a number of melting holes, and in America forced draught in the ash pits is universally used. The melting holes are sunk so that their top is at the working floor level, and there is a space provided in front of the ash-pit doors, so that the grate bars can be readily drawn from the holes for straightening, and the ashes easily shoveled out. This space is generally covered by a grating at the working floor

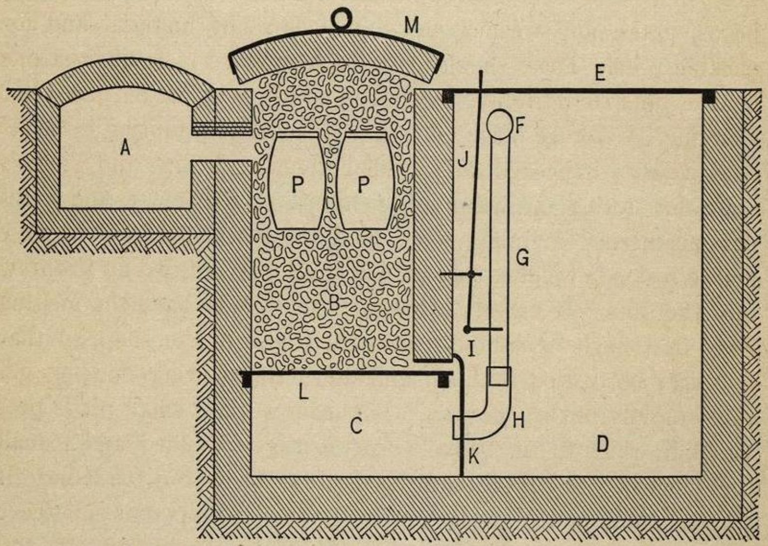

Fig. 1.—Anthracite coal melting hole. Vertical section. A, Flue; B, coal fire; C, ash pit; D, cellar; E, grating; F, G, H, blast pipe; K, ash pit door; I, J, blast damper; L, grate bars; M, cover; P, pots.

level, which serves the double purpose of giving light for the men to see what they are doing when removing ashes, and allowing any spilled steel to drop through without getting under the workmen's feet. The holes generally contain four pots, leaving room around the sides for fuel, and are deep enough to provide a bed of fuel from 18 in. to 2 ft. deep under the pots, when the tops of the latter are a few inches below the edge of the floor level. The covers of the holes are generally made in three sections so that they shall be light enough to handle easily.

The lay-out of such a shop is simple. The melting holes are generally lined up against one wall (or two walls) of the building, and the space in front of them covered with steel plates for piling plate scrap, heads, gates, and washed metal, for shoveling material and for packing pots. There should be room enough to pack at least one heat of pots comfortably, and have another heat packed ready for charging. A storage place for new pots, used pots waiting to be recharged, etc., is needed, and a small room with bins and grocer's scales for storing and weighing the alloys, such as nickel and ferrochrome, needed for alloy steels, and the cracked ferromanganese and ferrosilicon weighed into manila envelopes and tied up to throw into the pots. It may in some cases be best to have the melting holes in a single or double row in the center of the shop, so that pots can be carried both up and down the pouring floor to get them rapidly out of the way. For ladle work, a small pit is provided, in which to set the ladle when it it is being filled, and a small coal hole or a gas or oil burner is used for drying out the ladle. If a bottom pour ladle is used, stoppers, nozzles, stopper rods and sleeve bricks for the same require a storage room, where stoppers and sleeves can be put on the rods and a few kept ready for use. Since plants of this sort are generally very small, the exact lay-out is largely governed by the sort of building used, and common sense must govern the placing of furnaces, etc., so that the material can be brought to them and the steel carried away with the minimum of confusion.

For a furnace of five holes, four pots in a hole, two heats per shift, the crew will be one melter, one pot puller, one moulder (as he is called in the tool steel shops), and perhaps one helper to shovel coal and ashes, help pack pots, and do odd jobs.

Sheffield Coke Holes.—In the Sheffield crucible steel industry, where fine steel is produced, clay pots are generally used and coke used for fuel. Clay pots are generally somewhat smaller than