

TABLE LVI.—EFFECT OF ANNEALING.

Carbon.	Unannealed.			Annealed.		
	Tensile Strength or Maximum Stress per sq. inch.		Elongation per cent. on 2 inches.	Tensile Strength or Maximum Stress.		Elongation per cent. on 2 inches.
Per cent.	Tons.	Lbs.		Tons.	Lbs.	
.23	30.68	68,780	22.40	30.00	67,220	31.40
.37	38.18	85,300	8.20	36.70	82,220	21.80
.53	40.23	90,100	2.35	47.50*	160,480	9.80

Carbon.	Silicon.	Manganese.	Unannealed.			Annealed.		
			Tensile Strength per sq. in.	Elongation per cent. on 2 inches.	Reduction of Area.	Tensile Strength per sq. in.	Elongation per cent. on 2 ins.	Reduction of Area.
Per cent.	Per cent.	Per cent.	Tons.	Lbs.	Per cent.	Tons.	Lbs.	Per cent.
0.30	0.22	0.63	33.6	75,220	16	26.8	31.0	43.8
0.50	0.40	0.66	44.4	99,500	2	4.13	44.0	16.8

The following figures show the effects of "annealing" and "hardening" and "tempering":—

C.	Si.	Mn.	S.	P.	Fe.	Annealed.			Hardened and Tempered.						
						Tensile Strength per sq. in.		Elongation per cent. on 2 ins.	Tensile Strength per sq. in.		Elastic Limit per sq. in.	Elongation per cent. on 2 ins.			
						Tons.	Lbs.	Tons.	Lbs.	Tons.	Lbs.	Tons.	Lbs.		
Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Tons.	Lbs.	Tons.	Lbs.	Tons.	Lbs.	Tons.	Lbs.	Tons.	Lbs.
.35	.023	.252	.019	.038	99.35	34.4	77,080	17.6	39,500	27	48.9	109,560	29.06	65,090	16.5
.43	.028	.216	.023	trace	99.30	34.9	78,180	19.26	43,100	25.5	49.6	111,100	31.1	69,700	17.0

The first five results were obtained on castings and the last two on samples taken from a forged gun-jacket, hardened by quenching in oil at about 820° and re-heated to 650°. Annealing, especially in the case of high Carbon castings, does not seem to appreciably lower the maximum strength, although it decreases the elastic limit, and it largely increases both the elongation and the reduction of area.

* This is an abnormal result, although a slight increase in the maximum stress on annealing is not very uncommon.

CHAPTER X.

THE PRODUCTION OF SHEAR AND CRUCIBLE STEEL.

The Cementation Process.—Notwithstanding the immense development, in recent years, of the Bessemer and Siemens processes, special varieties of high Carbon steel continue to be made from what are known as "cement bars," by the converting or cementation process, which has so long been practised in the Sheffield district, and according as these carburised bars are piled and welded together, or fused in crucibles and cast into moulds, they are respectively known as shear or crucible cast steel.

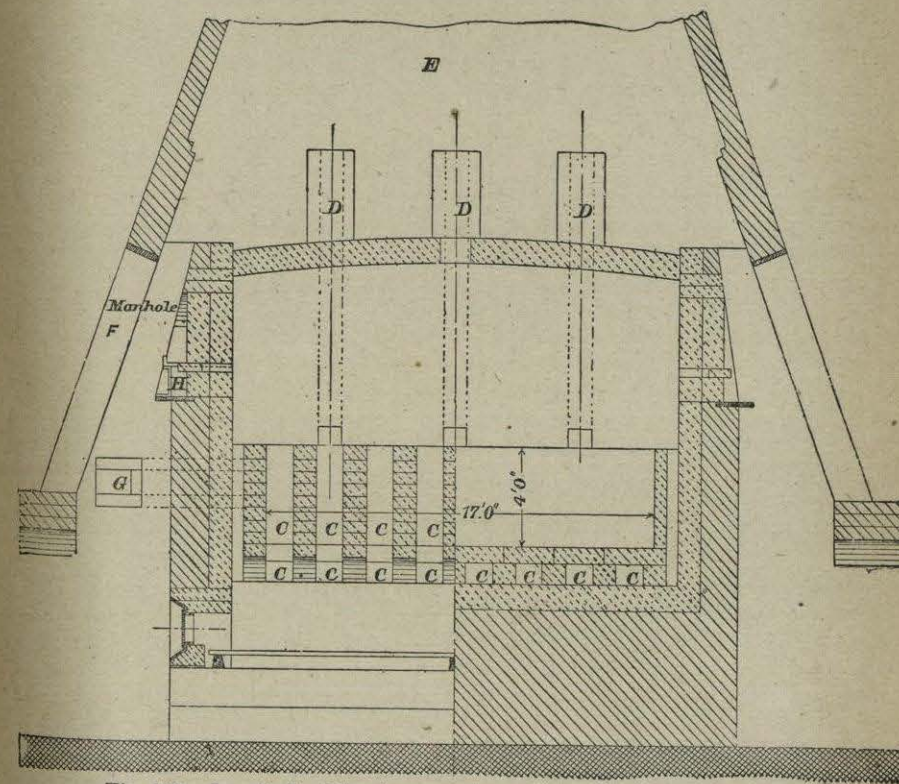


Fig. 183.—Longitudinal Section, part through the converting pot, and part through the flue.

The cementation process depends upon the well-known fact that iron, when heated with exclusion of air in contact with Carbon, absorbs that element in varying proportions which depend upon the time the operation lasts, and the temperature at which it is conducted.

Figs. 183 and 184 give transverse and longitudinal sections of an ordinary cementation furnace, in which wrought-iron bars are heated, in contact with Carbon, for varying periods according to the degree of carburisation required.

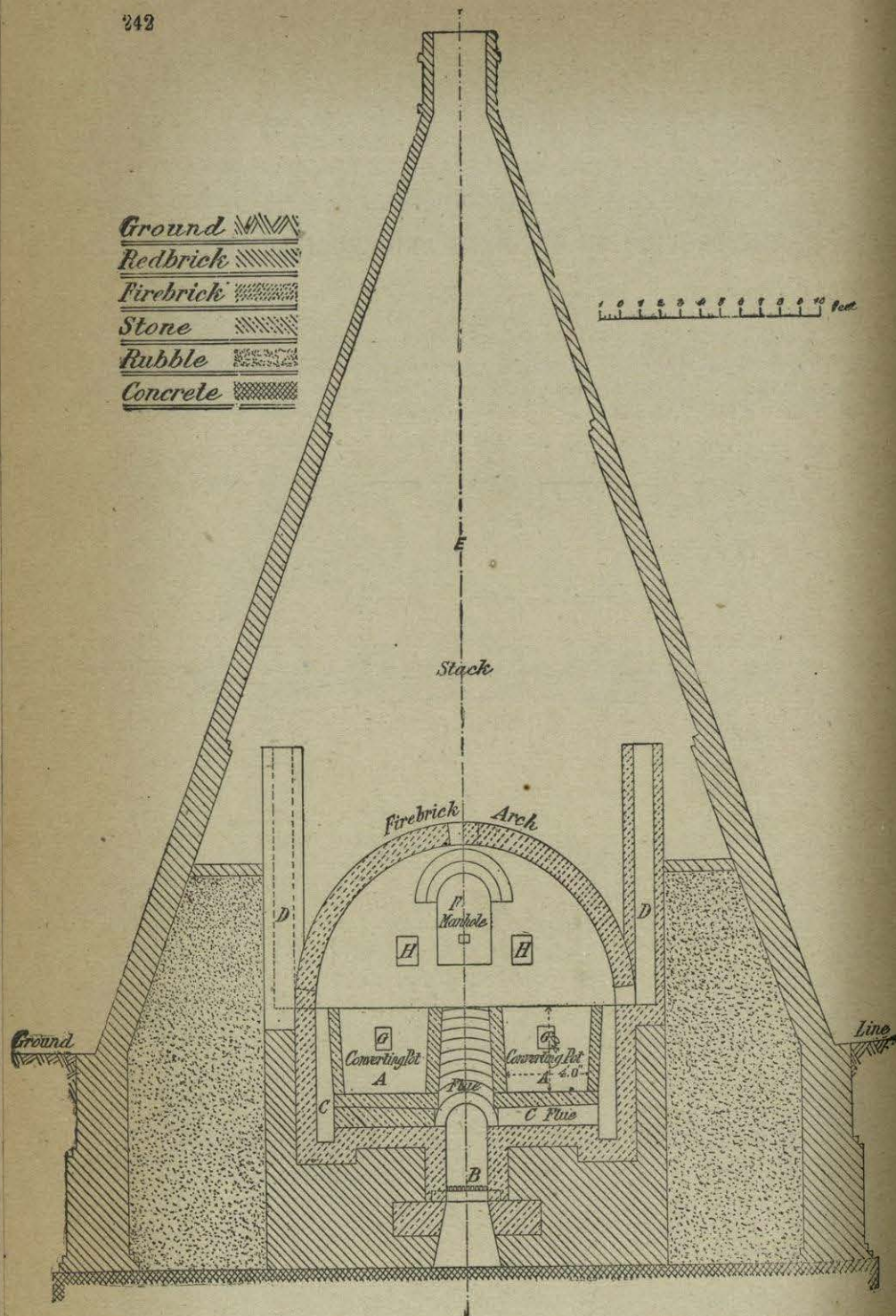


Fig. 184.—Transverse Section of Cementation Converting Furnace—A, Converting pots; B, firegrate; C, flues for distributing heat; D, short chimneys communicating with stack; E, conical hood or stack; F, manhole for introducing or withdrawing charge; G, holes for removal of trial bars; H, charging holes.

The converting pots, which form a part of the furnace, consist of two rectangular fire-brick or stone chambers, with fire-bars underneath, running the entire length of the pots, and the equal distribution of heat is effected by means of flues shown in the drawing. The size of the pots varies from 8 to 15 feet in length, and from 2½ to 4 feet in width, and they are generally about 3 feet deep, with a capacity of from 8 to 13 tons of bars. A manhole, which is bricked up during the cementing, is provided at the end of the furnace for charging and withdrawing the bars. There is a hole at one end of each pot, and a corresponding hole is left in the furnace for the insertion and removal of trial bars, which are withdrawn from time to time, and examined to see how the carburisation is proceeding.

The highest quality of cement bars is made from best Swedish iron, manufactured by the Walloon process. These are hammered bars, about 2½ to 3 inches wide, and ⅝ to ¾ inches thick, and are generally about

12 feet long, and the (L) iron, made from purest Dannemora iron ore,

is probably the brand which has the highest reputation for producing the finest qualities of steel. Numerous attempts have been made to use bars of exceptionally pure material, such as steel made from hematite in a basic Siemens furnace, and other extremely pure varieties of both iron and steel, but according to the experience of Sheffield steel makers an inferior product is always the result. This is certainly very difficult to explain, as, so far as chemical composition and purity of material go, the materials tried have, in many cases, been distinctly better than even the best Walloon iron.

Some allowance must no doubt be made for Sheffield manufacturers viewing with prejudice the results obtained by a departure from long recognised practice, but prejudice would hardly be strong enough to induce them, provided the comparatively low-priced English material gave equally good results, to pay many more pounds per ton for Walloon iron. This seems to prove that they have very good reasons for continuing to use Swedish iron, and that for some cause as yet unexplained, the Swedish iron produces a higher class product than cheaper materials of apparently better chemical composition.

Another point which requires explanation is that hammered bars are preferred to rolled bars for the best qualities of steel, and are said to give a better class of finished material. The process of cementation is conducted as follows:—The bottoms of the pots are first covered with a layer of charcoal on which the bars are laid on their flat sides, separated from each other by about half an inch of charcoal, then another layer of charcoal is placed on these and another layer of bars, these alternate layers of bars and charcoal being repeated until the pots are full, when the whole is covered with a final layer of charcoal. The top of the pot is then closed by an arch made of wheel swarf—i.e., a mixture of silicious particles and partially rusted steel, obtained from the grindstones in cutlery grinding—which at the heat of the furnace frits together, and forms a practically airtight lute. The charcoal, prepared from the harder woods, is usually preferred, but this is not essential, and, according to Bauerman, birch is used in Sweden, beech in Rhenish Prussia, and oak in England. Before use, the charcoal is passed through a ½ or ¾ inch mesh.

When the furnace is charged the manhole is bricked up, all small openings tightly luted with clay, the fire lighted, and the temperature of the furnace raised gradually to a red heat, which usually takes about twenty-four hours. After about two or three days the furnace will reach its full temperature, and this is maintained for a period of from 7 to 11 days, according

to the grade of steel required. For so-called mild heats the furnace is fired for 7 to 8 days; for medium heats about 9½, and for very high Carbon heats about 11 days. At the end of this time the fire is banked up, and the whole furnace allowed to cool down for a period of about 14 days.

The bars when removed from the cementation furnace are covered with surface blisters, and are known as "blister bars," or "blister steel." These blisters should be small and equally distributed over the bar, and should not run along special lines.

Grades of Cement Bars.—Cemented bars are generally classed in seven grades, according to the percentage of Carbon they contain, and are numbered from 1 to 6, grade 7 being called "doubly converted bars." They are broken and graded according to fracture. Sometimes, owing to the carelessness of the workmen, or to defects in the furnace, the pots become too highly heated, with the result that the surface of the bars is slightly fused, and these are known as "glazed bars." If by any chance the pots should crack, or any of the fireclay lutes give way so that air gains access, the bars are liable to become oxidised, and are then known as "aired bars." The greatest skill is shown by experienced men in sorting these bars, and they are able to detect very slight variations in the Carbon contents.

Micro-structure of Cement Bars.—Very mild bars contain an unaltered central core of mild steel known as "sap," and very hard bars are easily distinguished by being what is known as "flaked," as, on fracture, they present bright cleavage planes, which are due, according to Professor Arnold, to the fracture taking place along the junctions of the cementite or Fe₃C walls, enveloping the crystalline grains of pearlite or true steel. Professor Arnold,* in a very exhaustive paper on the "Micro-chemistry of Cementation," gives a series of analyses of cemented bars, showing the variation of the Carbon from the outside to the centre of the bars, and also illustrates the same point by a beautiful series of coloured micrographs.

The iron used in the experiments was Swedish-Lancashire hearth bar iron, made from Dannemora pig and branded "Little S," and had the following composition, which may be taken as typical of Swedish bar iron:—

Carbon,	0.050
Silicon,	0.037
Sulphur,	0.006
Phosphorus,	0.012
Manganese,	0.108
Copper,	trace
Arsenic,	0.007

The carbon in cement bar varies considerably from the outside to the centre, but the following were the mean Carbon contents of the bars after cementation:—

Material.	Mean Carbon.	Remarks.
No. 2 bar,	Percentage. 0.45	Carbon in three distinct layers.
No. 3 bar,	1.13	" "
No. 4 bar,	1.33	Carbon in two distinct layers.
No. 5 bar,	1.60	Practically uniform.
No. 6 bar,	1.80	" "
Doubly converted aired bar,	1.90	Fairly uniform.
No. 4 bar (after airing),	1.04	...

* Iron and Steel Inst. Journ., 1898, vol. ii., p. 185.

No. 2 bar in these experiments is said to have been somewhat milder, and No. 3 somewhat harder than the average Nos. 2 and 3. Cuttings were taken from the outside of bars Nos. 2, 3, and 4, to the centre, at varying depths, increasing in the case of No. 2 by .02 of an inch, and in the case of Nos. 3 and 4 by .04 of an inch, and the analyses of these are given in Table lvii., and show very clearly the gradual penetration of Carbon into the bars.

TABLE LVII.

Cut No.	Depth into Bar in inches.	MEAN CARBON PER CENT.			
		No. 2 Bar.	No. 3 Bar.	No. 4 Bar.	No. 4 Bar (aired).
1 (outside),	0.02	0.98	...	...	0.00
2,	0.04	0.95	1.40	1.50	0.00
3,	0.06	0.76	...	...	0.30
4,	0.08	0.63	1.26	1.45	1.20
5,	0.10	0.50	...	...	1.45
6 (median),	0.12	0.39	1.15	1.27	1.45
7,	0.14	0.37	...	...	1.45
8,	0.16	0.31	1.10	1.29	1.40
9,	0.18	0.18	...	...	1.38
10,	0.20	0.15	0.98	1.29	1.38
11,	0.22	0.10	...	...	1.35
12 (centre),	0.24	0.10	0.88	1.15	1.16
Mean carbon in half the bar, . . . . .	...	0.45	1.13	1.33	1.04

Aired Bars.—If, as already pointed out, air gains access, by any means, to the bars during conversion or cooling, and the surface becomes more or less oxidised, such bars are known as "aired bars." An analysis of a No. 4 bar in layers of .02 of an inch thick, from outside to centre, is given for comparison with the normal No. 4 bar, and it will be seen how the Carbon has been entirely removed from the surface of the bars. The analytical results in Table xxxix. are fully confirmed by the micro-photographs, for which the student must be referred to the original paper. Bars Nos. 5 and 6 show no difference in Carbon percentages between the outside and centre, being practically uniform throughout. Double converted bars, which sometimes contain slightly over 2 per cent. of Carbon, are obtained by two conversions, but Professor Arnold says that, so far as his experience goes, he has not found it possible to introduce much over 2 per cent. by cementation even after ten conversions.

In Sheffield the six grades of steel referred to have received, for convenience, the names given below, and, according to Mr. Seebohm,* contain about the following percentage of Carbon:—

1. Spring heat, 0.50 per cent.
2. Country heat, 0.63 "
3. Single shear heat, 0.75 "
4. Double shear heat, 1.00 "
5. Steel through heat, 1.25 "
6. Melting heat, 1.50 "

These percentages of Carbon are somewhat lower than those found by Professor Arnold in the bars he examined, but probably different makers

* Iron and Steel Inst. Journ., 1884, p. 372.

have slightly different ideas as to the exact percentage of Carbon it is advisable to put in the various grades.

The Origin of the Blisters.—The cause of the production of the blisters on the surface of converted steel has in time past led to much discussion, but was finally settled by Dr. Percy, who, writing in 1864, suggested that they were due to the action of Carbon on the intermingled slag in the bars of iron used. This slag consists of ferrous silicate with more or less Oxide of Iron, and the result of the action of Carbon is the production of Carbon Monoxide in the interior of the bar, which, being at a high temperature, would be soft and readily expanded by the gas so produced. When the suggestion was made there was no experimental evidence of its correctness, but this Dr. Percy was afterwards able to supply,* and to prove that when iron which has been remelted, and so freed from intermingled slag, is subjected to the cementation process, no such blisters are produced, although in other respects the metal is converted as usual. Sir W. Siemens, in discussing the above results,† also stated that he had invariably found that when mild steel is subjected to cementation no blisters are produced, although hard steel is obtained as usual.

The Diffusion of the Carbon.—The actual way in which the diffusion of Carbon through the metal takes place, whether diffusing as Carbon in the same manner as a solid gradually diffuses when dissolved in a solvent, or whether as Carbides of Iron, is still a matter which is open to discussion, and much has been written in support of both views. As bearing on this question the experiments of Messrs. Metcalf and Langley may be cited, which clearly showed that Carbon is able to readily travel about in steel bars at high temperatures, although they did not throw much light upon the question whether they diffused as a Carbide or as Carbon. In these experiments a bar of high Carbon steel was placed in the centre of a mould, and mild steel was poured around it; the compound piece was then rolled down into a square bar. In a transverse section of the compound bar resulting, the hard interior strip could be plainly distinguished both by the difference in the action of the cutting tool upon it, and by etching with nitric acid. The outline of this hard centre was carefully marked off by means of a centre punch with holes rather less than $\frac{1}{16}$ of an inch in depth. The piece was then closely wrapped in a sheet-iron covering and exposed to a heat somewhat below the melting point of copper for five hours; it was then cooled and the metal planed down nearly to the bottom of the punch marks. The Carbon was then found to have travelled outwards from the hard interior, and to have formed a nebulous fringe in the softer steel. A similar observation had been previously made by Sir F. Abel, who annealed some thin steel discs containing about 1 per cent. of Carbon in a closed cast-iron box between two wrought-iron plates for about 24 hours. On afterwards analysing the discs it was found that the Carbon was reduced to 0.1 per cent., thus showing that this element had to a great extent passed out of the steel and been absorbed by the wrought iron.‡ Experiments by Mr. G. P. Royston also showed that if steel and wrought-iron plates were placed in close contact, the wrought iron gained in weight and the steel lost, and this gain in the wrought iron corresponded almost exactly with the loss of weight of Carbon in the steel when the plates were heated *in vacuo*. These facts have been generally confirmed by a very systematic series of experiments conducted by Messrs. Arnold & McWilliam§ on the diffusion of elements through steel at different temperatures. Cylinders of pure iron, bored with

* *Iron and Steel Inst. Journ.*, 1878, vol. i., p. 116. † *Ibid.*, p. 122.

‡ *Trans. Inst. M.E.*, 1883, p. 57.

§ *Iron and Steel Inst. Journ.*, 1899, vol. i.

the greatest care, were shrunk on to high Carbon steel cores and heated *in vacuo* for ten hours at a temperature of 1,000° C., when very considerable diffusion was found to have taken place, the Carbon having increased from .05 to .50 in one case in the outside jacket. In a further series of experiments it was shown that no diffusion took place from high Carbon cores with 1.78 per cent. C. to the low Carbon jacket during six hours below 740° C., but that it became just perceptible at 785° C., and that at 855° the diffusion took place readily. When, however, the Carbon in the outside jacket was increased to .89 per cent., the diffusion from the internal core to external jacket did not apparently take place until a higher temperature was reached—viz., 960° C. Although these results and others given in the paper are of the greatest interest, they do not settle the question of the manner of diffusion of the Carbon, and further data are required before this point can be fully and profitably discussed. These facts, however, seem to indicate that, as Professor Arnold says, it would be possible to convert iron up to .90 per cent. Carbon at a temperature of about 800° C., but that to produce bars with higher percentages of Carbon a temperature of at least 950° C. is required. In practice, the actual temperature is about 1,000° C., and according to Bauerman, who has studied the process very carefully in all countries where it is in use, the action is much more rapid at about 1,100° C., or just above the melting point of copper.

Spring Steel.—The blister bars, after conversion and separation into the various grades, are drawn out under the hammer or rolled at a yellow heat, and are then known as "plated bars" or "bar steel." Formerly springs were almost entirely made from these bars, and they were known as spring steel, but now they are either piled and welded for shear steel or cut up before hammering and melted in pots to form cast steel.

Shear Steel.—In manufacturing shear steel, plated bars are broken into suitable lengths, six piled together into what is known as a faggot, covered with fireclay and borax to prevent oxidation of the Carbon, heated in a hollow fire, and drawn out under the hammer to a bar. The bar is then known as single shear. In many cases the homogeneity of the steel is further increased by breaking the hammered bar through the centre, doubling it upon itself, re-heating, and re-hammering down to the required size; it is then known as double shear. Notwithstanding that the blooms during re-heating are protected by slag formed by the clay covering, the Carbon is always more or less oxidised, and the manufacturer is perfectly aware of this, and always selects a grade of bars of higher Carbon than he requires in his finished product, and he knows by experience exactly what allowance to make for this when he has trustworthy workmen. The single or double shear bar is afterwards, by forging and rolling, drawn into thin strips suitable for cutlery. Although no number of pilings and hammerings can ensure the same homogeneity that is obtainable with a metal that has been fused and cast, still for such purposes as the manufacture of high-class table cutlery, butchers' knives, and any class of knife which has an iron back with a cutting edge welded on, shear steel is superior to the finest cast steel, and has been able to hold its own against all comers. The word shear was originally applied from the fact that the blades of shears, formerly used for cropping woollen cloth, were always made as above described.

Case Hardening.—This process, which finds numerous applications in constructive engineering, is, like the surface carburising of armour plates, a special application of the cementation process. The object in the majority of cases is to obtain a hardened steel surface, while retaining a tough ductile

core of mild steel, but sometimes it is to improve the appearance of the article, for, with the increase of Carbon, tints and mottling may be obtained, which are impossible in lower Carbon steels. Various nostrums have been used for case hardening, and numerous attempts made to surround the process with mystery, by pretending that its success depends upon the use of a certain liquid for quenching, but the particular liquid used has no influence whatever, except in so far as all liquids have a greater or less hardening effect according to their conductivity and specific heats.

For case-hardening processes, various carburising materials are used, these include (1) solid materials, such as animal charcoal, bones, charred leather, compositions sold under various names and consisting of carbonaceous matter, and certain cyanides and nitrates, mixtures of barium carbonate and wood charcoal, &c.; (2) liquid materials, such as molten cyanide of potassium; (3) gaseous materials, such as illuminating gas, hydrocarbon vapours, &c. The only essential conditions for success are the use of a suitable form of Carbon, and care in heating to the required temperature, and for the length of time necessary to produce the depth of carburisation required for the particular class of work in hand. When solid carburising materials are used, these should be sifted free from dust, and the grains should be of uniform size. The addition of a small quantity of heavy hydrocarbon oil to the powder is an advantage, and prevents the absorption of moisture.

The hardening pots are made either of cast iron or wrought iron, the former are cheaper in first cost, but the latter last much longer. The pots should not be larger than necessary for the size of work in hand, and for small articles should be about $12 \times 10 \times 8$ inches. The pots must each have a close-fitting inside lid. There should be a layer of about $1\frac{1}{2}$ inches of the powder round each article to prevent it touching the others or the sides of the box, and the packing is finished with a layer of $1\frac{1}{2}$ inches on the top. The contents of each pot is made as compact as possible, the lid is put on, and the joint all round is well luted with clay. The charged boxes are now placed in a muffle furnace capable of being raised to about $1,000^{\circ}$ C., and maintained at that temperature with great regularity. These muffles may be coal or gas-fired. The depth of case hardening, and also the amount of Carbon contained in the case, will vary with the temperature and length of time the operation lasts. For small work at a temperature of $1,000^{\circ}$ for six hours a case about $\frac{1}{16}$ inch, containing about 0.8 per cent. of Carbon, will be obtained. After the desired time has been given for the absorption of the Carbon, the pots are withdrawn from the furnace, and allowed to become quite cold. The articles are then removed, and are brushed to remove all adhering matter. If the pots have been properly packed and luted up, the articles should be quite white, the more inclined to redness the articles are, the more imperfect has been the packing and sealing of the pots. The case-hardened articles are now placed in a muffle furnace and heated to about 800° C., and then quenched in cold or tepid water or oil, according to the purpose for which they are required. In some cases the whole contents of the box are directly emptied into water or oil, the separation of the articles from the powder being made by suspending a sieve a few inches below the surface. If the appearance of the articles is important, care must be taken that they are not exposed to the air in the fall from the box into the water, otherwise oxidation will result, and the skill of the workman is shown in avoiding this. On the other hand, many different tints can be given to the work by dropping it from a height, say, 3 to 6 feet, when oxidation neces-

sarily takes place, and a blue or streaked black coating will result. The colour can be varied by forcing air into the bath with the inlet water, so that the work comes with a further supply of Oxygen while chilling. The article is then taken out of the water and rolled in dry and warm sawdust, and then oiled. If the character of the steel to be case hardened is unknown, a test piece, in the form of a rod, may conveniently be used, this being stuck through a hole in the lid of the box, and withdrawn for testing as the operation proceeds.

The theoretical considerations of case-hardening processes have received considerable attention during the last few years, and many workers have recognised the important effect that nitrogen has on the penetration of the Carbon. In the case of non-nitrogenous material, such as sugar, charcoal, or anthracite, it is usually assumed that case hardening is effected indirectly by the air contained in the boxes forming Carbon Monoxide, which gas reacts with the iron, giving up some of its Carbon and forming Carbon Dioxide, this latter gas reacts with a further portion of Carbon, producing still more Carbon Monoxide, and so the process is continuous. Braune* and Petrón and Grabe † have shown that the Nitrogen content of steel is increased on cementing, and the last-named workers demonstrated that, in cementing, the Nitrogen content increases proportionately with increase in Carbon content in the steel, but only up to 1.0 per cent. Carbon.

G. Shaw Scott ‡ carried out a series of experiments on case hardening under similar conditions, with non-nitrogenous materials, such as anthracite and hard coke, and with nitrogenous material, such as charred leather, with the result that the depth of case hardening was increased in the ratio of 10 to 1 when using the charred leather.

S. A. Grayson § has also investigated the action of different case-hardening materials, and has come to the conclusion that it is necessary to classify the different compositions both by the Carbon per cent. obtained in the case, and also by the graduation of the Carbon diffusion, this classification is necessary because the various compositions are each suitable for special classes of work. A high Carbon case would be very efficient for work where the pressure is fairly constant, but would be unsuitable for parts which had to resist repeated shocks, because of the strong tendency of the high Carbon case to chip or even peel off. The following are analyses given by this author for different case-hardening materials:—

	Bone.	Charred Leather.	Hardenite.
	Per cent.	Per cent.	Per cent.
Carbon,	8.0	69.0	44.0
Volatile matter and Hydrocarbons,	26.5	15.2	14.1
Nitrogen,	3.5	3.8	0.9
Ash,	60.0	3.5	37.5
Sulphur,	0.1	0.55	Trace
Moisture,	2.0	8.0	3.5

The "Hardenite" material consists of about 40 per cent. barium carbonate and 60 per cent. of charcoal. The chief action of the barium carbonate

* *Bihang till Jernkontorets Annaler*, 1907, p. 191.

† *Ibid.*, vol. lxi., p. 16.

‡ *Journ. Iron and Steel Inst.*, 1907, No. 3, p. 130.

§ *Ibid.*, 1910, No. 1.

seems to be due to the decomposition which takes place when this substance is heated in the presence of charcoal, barium monoxide, and carbon monoxide being formed, this carbon monoxide then takes an active part in the carburising.

Various methods have been adopted for the use of potassium cyanide as a case-hardening medium, the simplest method for special work and skin-hardening is to heat the article to almost a white heat, soak it into a cake of the cyanide, then reheat and plunge into water. A more satisfactory method of case hardening with potassium cyanide is to melt the cyanide—sometimes mixed with common salt to reduce the amount of poisonous vapours evolved—in a wrought-iron or cast-iron pot, and to soak the articles in the bath for a length of time determined by depth of case required, by this means it is possible to get quite deep case hardening. After soaking for the necessary time, the articles are removed, and either quenched in water or cooled, reheated, and quenched. Small iron parts are sometimes case hardened by soaking for 30 minutes in a fused bath consisting of 1 part of prussiate of potash and 10 parts of common salt, and then quenching in water.

Several processes and special furnaces have also been devised for case-hardening by means of gases; in these cases the work is brought to the correct temperature, and the Carbon-laden gases from the producers are introduced. J. C. Olsen and W. S. Weiffenback* investigated the case-hardening of steel by gases, and found the following to be the order of carburising ability—carbon monoxide, acetylene, methane. G. Charpy† has studied the action of carbon monoxide as a case-hardening medium, and found that cementation was possible at as low a temperature as 560°; he found, however, that between this temperature and 750° the cementation action was accompanied by a deposition of a layer of pulverulent Carbon on the specimen; above 750° there was no deposit of Carbon, but the rate of cementation increased up to a temperature of 900°, beyond which there was no apparent increase.

As an example of the utility of case hardening may be instanced the case of a crank spindle for a bicycle, where a combination of lightness, toughness, and wearing surfaces which will resist a file, are wanted. A mild steel may, therefore, be taken and machined to the shape required; it is then case hardened, and, on account of the distortion frequent in the latter process, is finally ground to finished size. The soft core of the metal, which is unaltered, will insure the toughness of the article.

* *Iron Age*, vol. lxxxiv., pp. 120-121.

† *Revue de Metallurgie, Memoires*, vol. vi., pp. 508-518.

CAST OR CRUCIBLE STEEL.

However carefully the steel converted bars may be selected, welded and re-welded, there is always a certain want of uniformity, and to obtain a thoroughly homogeneous material it is necessary to melt the materials in pots or crucibles.

Pot Melting.—The process of melting in pots was introduced into Sheffield about 1740 by Huntsman, and very little variation has taken place since in the method of carrying out the operation. A sketch of a

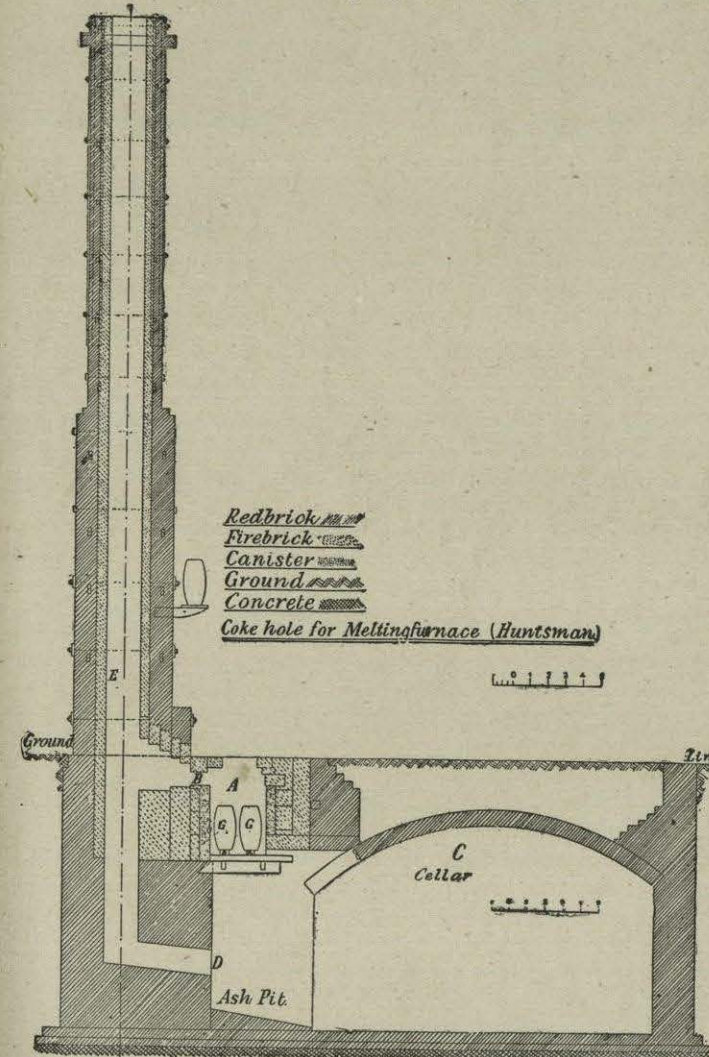


Fig. 185.—A, Melting hole or fire hole; B, flue; E, chimney; D, opening communicating with chimney flue, which can be partially or entirely closed by a brick or sheet of paper to control the draught.

melting furnace is given in fig. 185, and it consists essentially of a "melting hole," which is a rectangular chamber, about 3 feet deep, and from 1½ to 2 feet square, lined with fire-brick and rammed ganister. The top of

the furnace is at the level of the floor of the casting house, and is covered with a square of fire-brick, set in an iron frame with a projecting handle. The grate bars and ashpit are sunk below the floor, and an arched vaulted cellar below enables the workmen to gain access to these. Each melting hole is connected by a flue at the top with a stack which serves for five or six furnaces, usually arranged in a line on each side of the casting house, thus leaving the centre of the floor clear for casting operations.

The crucibles are made either of fireclay or of Graphite or Plumbago, and the greatest care is taken in the manufacture of these, as faulty pots mean very serious losses to the manufacturer. In this country clay crucibles are almost invariably used, and they are usually made in a shop adjoining the casting house. In Sheffield the pots are generally made from a mixture of Burton and Stannington clay, sometimes mixed with a certain proportion of Stourbridge clay, and a little China clay; a small quantity of ground coke and old pots is also generally added. The clays have to be very completely ground, and most thoroughly mixed together. This is usually done by treading in a trough, the pot-maker and his assistant kneading it with bare feet. Too much care cannot be exercised to insure the perfect working of the clay, as it is absolutely impossible to make good cast steel if the pots are defective, and in fact pot-making is an important branch of the manufacture of cast steel. The well-worked clay is cut into balls of sufficient size to make one pot, and moulded in an iron "flask," with well-fitting loose bottom, by pressing down a wooden or cast-iron plug. Both "flask" and "plug" must be well oiled, and the latter is centred by a pin at the bottom, which passes through the loose bottom of the flask. The plug is alternately raised and lowered until the clay is worked up to entirely fill the annular space between it and the flask, and then finally driven down with a mallet, after which it is withdrawn by turning it round. The edge of the crucible having been trimmed, it is placed upon a post, when the flask being released its weight causes it to drop, leaving the crucible standing upon the loose iron bottom of the flask, on the top of the post (fig. 186). The top of the crucible is now forced in by means of a conical mould to give it the barrel shape shown in the sketch (fig. 187). The crucibles are very carefully dried for two or three days on the shelf in the pot house, and then transferred to a shelf in the casting shop, near the flues, where they are dried for a period of at least ten or twelve days, and preferably for a month or six weeks. Each pot lasts a single day, can be used three times, and contains about 56 lbs. of metal for first heat, 44 lbs. for second, and 38 lbs. for the third. The object of reducing each successive charge is that the surface of the molten metal shall be at a different level in the pot, because the "flux" or scum, which floats on the surface, rapidly attacks the Silica of the pot, and cuts it away.

Clay pots are specially suitable for mild steel, as they do not carburise the metal, while it is almost impossible to get very mild crucible steel of uniform quality out of Plumbago pots. In Styria, on the Continent generally, and in America, Plumbago pots are commonly used; they consist of Graphite, with sufficient refractory argillaceous matter, to give the necessary cohesion during manufacture.

In this country Ceylon Graphite is preferred for the manufacture of Plumbago crucibles. It is carefully hand picked, then ground and sieved, mixed with fireclay in suitable proportions, and allowed to "mellow" before use. Selected Ceylon Graphite contains about 90 to 95 per cent. of Carbon, and as crucibles made from this material stand four or five charges, their longer life about balances the extra cost involved in their manufacture. But there is a disadvantage in using a pot a number of times, since the pots give up a greater proportion of Carbon to the first charge, and less with each

succeeding melting. Hence the product is apt to be irregular unless the

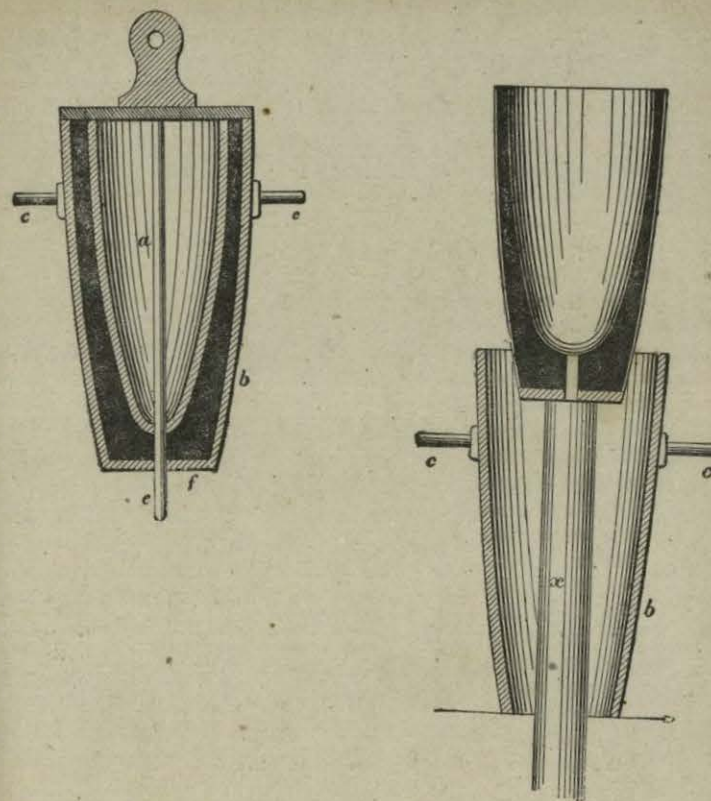
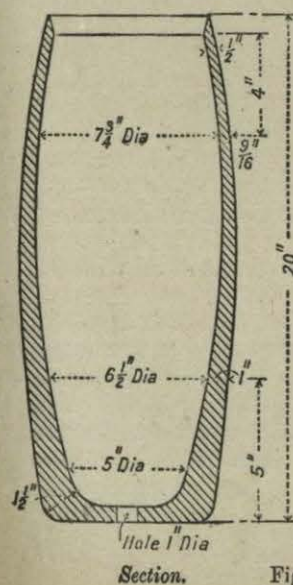
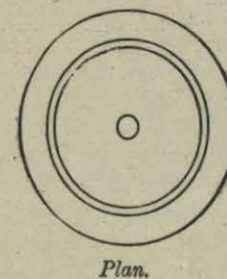


Fig. 186.—Manufacture of clay crucibles—*a*, Wooden plug; *b*, flask or mould; *c*, trunnion arms on flask; *e*, pin for centering plug; *z*, stripping post.



Section.



Plan.

Fig. 187.—Crucible, as used in Sheffield.

charges are arranged so as to meet the difficulty, which is practically almost impossible. As the crucibles are expensive, there is also the temptation to get the maximum number of charges from each pot, and thus with the last heat the walls sometimes become dangerously thin, and the charge has to be withdrawn before it is thoroughly "dead" melted.

Several moulding machines have been designed for crucible making, and are used in America, and in some large potteries in England, where crucibles are made a speciality, but as far as English practice goes, when the pots are made at the steel works, they are generally moulded by hand, although some steel makers have introduced moulding machines into their works.

Methods of Manufacture.—Cast steel is made of different “tempers,” and may vary in percentage of Carbon from .5 per cent.* to 2.0 per cent. or even more, according to the purpose for which it is required, and the percentage of Carbon may be arrived at in various ways.

For the great majority of purposes, when the highest class material is required, there can be little doubt that the best method is to use most carefully-selected blister steel—taking care to exclude all bars which are harder or softer than the temper required, and all “flushed” or aired bars—and to melt it in the crucible. Crucible steel made in this way will combine the greatest amount of hardness, with the maximum amount of elasticity when hardened; but there are two or three other ways by which very high class material may be made. Instead of blister steel best “cut bar iron,” that is Swedish iron bars before converting, may be melted, and “fetched up” to the required “temper” by putting charcoal in the pot, or the purest varieties of broken pig-iron may be “let down” by melting it with cut bar iron. Another method which, for many purposes, is best of all, is to select blister steel of slightly harder “temper” than that required in the finished steel, and then to “let it down” to the exact “temper” by the addition of a small quantity of somewhat milder scrap.

When steel is made from unconverted bars they are cut up by shears into triangular pieces about 3" × 3" and charged into the pot with varying amounts of charcoal, from ½ ounce to 8 ounces per charge, according to the temper required, and when the metal is completely melted a quantity of Spiegeleisen is added. In case of very mild temper steels sufficient carburisation is often affected by melting in Plumbago pots without any additions of Carbon, the Graphite of the pots with the Carbon of the Spiegel added producing the required “temper.” The method of making cast steel by melting malleable scrap iron with charcoal and Oxide of Manganese was introduced into Sheffield by Mushet in 1801, and is still largely practised. Heath’s process consisted in the addition to the charge of malleable scrap iron, of Manganese more or less reduced by Carbon at a very high temperature, or of a mixture of black Oxide of Manganese with carbonised pitch or resin.

In 1839 Mr. W. Vickers patented the use of a mixture consisting of 100 lbs. of wrought iron in the form of turnings or borings, 3 lbs. of black Oxide of Manganese, and 3 lbs. of the best ground charcoal. In recent years there is no doubt that considerable quantities of crucible cast steel have been made from mild Bessemer or Siemens scrap instead of best Swedish “cut bar iron,” but the quality is always inferior, and cannot compare with the best steel made from selected cement bars, or with Styrian open hearth bars.

Whatever variation there may be in details as to the mixture, the process is carried out as follows:—The pots, previously well dried and annealed by heating to redness in an annealing grate, are placed in the furnace upon a circular disc of fireclay or a fire-brick resting on the fire-bars. The fire is then made up level with the top of the pot and the heat gradually raised for about half an hour, after which a little sand is thrown into the pot to fill the hole made by the central pin in moulding, and this also frits the pot to the

* Crucible steel is made with a much lower percentage of Carbon than .5 per cent., for some special purposes as low as .10, but .5 per cent. is about the limit for “cast steel” as used for tools.

fireclay disc. The broken blister bars or scrap, charcoal, &c., as the case may be are then put into the pot through an iron funnel called a “charger,” the lid placed on the pot, the furnace filled with coke and the fire urged. In about fifty minutes the fire is poked down and made up again with more coke, and when this is burnt off the lid is removed and the pot searched with an iron rod to see whether the charge is completely melted, and if not the fire is poked down and the furnace again filled up with coke. The temperature of the furnace is regulated by the “puller out” by inserting bricks in the melting or cellar hole flue (D, fig. 185). The cellar hole flue is also often controlled by the somewhat crude but effective method of closing the hole by means of a sheet of paper which is placed over the hole, and when it is expedient to admit more air a hole is made in this with an iron bar, and it is curious to note the ease with which a skilful man will regulate the heat by this means. After the second or third fire has burned down, the head melter carefully inspects the pots and gives final instructions to the “puller out” as to when the metal is ready for “teeming.” At the word from the melter the pot is removed by means of tongs from the furnace to the furnace floor, cleaned from coke and slag on the outside, the lid taken off, and the scum or slag skimmed off the surface of the molten steel. This is then poured into a cast-iron mould made in two halves, clamped together with rings and wedges, to facilitate the withdrawal of the ingots afterwards. To prevent the ingots adhering to the mould, the interior of the latter is reeked or covered with a wash of coal-tar soot before using. Immediately after teeming the pots are taken back to the melting hole, cleared from the adhering clinker on their sides and bottoms, and replaced in the fires when they are ready for another charge. The first heat usually takes about 4½ to 6 hours, but the second and third will not, as a rule, take more than 2½ to 3 hours.

Melting the Steel.—The melting of the higher qualities of steel is a process which requires the greatest judgment and skill, and the quality of the final product will to a very great extent depend upon the technical skill and sound judgment of the head melter. If the steel is not kept sufficiently long in the furnace—that is to say, if it is not properly “killed”—it will teem fiery and produce a honeycombed ingot, and if it is poured at too high a temperature the same result will follow. If kept too long in the furnace the steel will teem dead, and will be brittle if hard steel, and deficient in tensile strength if a low Carbon steel, and the fracture of the ingot will have what is known as a “scorched look.” If, again, the molten steel be chilled too much before it is cast, detected by the stream skimming over as it is teemed, the ingot will be honeycombed, and the fracture will be dull in colour. Should a piece of coke by any chance find its way into the pot during the melting, the ingot will have a bright sparkling fracture; in technical phraseology, it will be said to “stare,” and will work “hot short” under the hammer.

There is always a tendency for mild steel to rise in the ingot moulds, and the mouth of the ingot mould is closed with a plug of cast or wrought iron or with sand to prevent, as far as possible, the top of the ingot from becoming spongy. In ingots with 1 per cent. or more of Carbon, if properly melted, the steel in the centre of the ingot will settle down as it cools, leaving a hollow space in the middle of the top of the ingot known as a “pipe.” This should be not less than 3 to 5 inches deep.

Treatment of Ingots.—The waste in crucible steel manufacture during melting varies somewhat, but is generally at least 10 per cent. of the charge. The ordinary sizes of ingots are 2½ and 3 inches square and about 30 inches long, and other sizes are made up to 12-inch ingots, but these are only cast when specially required, as these larger sizes have to be clogged, and involve

extra expense in the subsequent treatment. When large and heavy ingots are required several pots are employed. In special cases the contents of a large number of crucibles are poured into a ladle from which the ingot mould is filled, care being taken to have a constant stream of fluid steel from the beginning to the end of the cast. In this way castings weighing as much as 70 tons have been made. When the ingots are cold they are topped—that is to say, the hollow part or pipe is broken off until the ingot shows a sound fracture. The ingots which have been improperly melted are rejected, and the others are graded according to Carbon contents. Between the range of 1 to 1.5 per cent. of Carbon an experienced man will readily be able to detect by fracture a difference of .1 per cent. of Carbon.

The next operation is to reduce the ingot to the form or section required by the consumer, and for this purpose it must be re-heated and forged or rolled. As the value of the steel for the particular purpose for which it was manufactured depends almost entirely upon its Carbon content, it will be obvious that the greatest care must be taken not to oxidise the Carbon to any appreciable extent during reheating, and all overheating must be most carefully avoided. With this object in view the steel must be sprinkled with ground fireclay or sand and borax before being placed in the furnace, and continually turned round in the fire to ensure equable heating quite through the bar, or until it is thoroughly “soaked.” On the other hand, it is very important not to subject the ingot to too long a soaking, as this rapidly deteriorates the quality of the material. Whether the ingots are rolled or hammered depends on the shape and size of the finished bar. Almost all the manufacturers, even the smaller ones, have facilities for forging at their works, but it is only in a few of the larger works that the cogged billets can be rolled. There are a large number of small manufacturers, and as tool steel is a relatively costly material, with a limited demand, it has been found desirable to provide public mills and forges where the ingots can be rolled or forged at a trade list price, and even the largest firms send their ingots to these when making unusual sizes. The use to which a bar is to be put and the section and size usually determine whether it is to be rolled or hammered. Thus steel to be used for taps is forged so as to give greater density, while that for punches is rolled to ensure greater uniformity. Best squares, from sizes of half-an-inch and upwards, are always forged; octagons are also forged from a square bar or rolled into square bars and planished afterwards under the hammer. Small rounds are best rolled, while triangular sections are always rolled, as it is so much easier to produce the required sizes in this way. Small flats are always rolled; large flats are also often rolled, though sometimes they are forged, as this gives sharper and better defined edges. In forging a steel bar one-half of the ingot is heated and forged, while the other end is held in a pair of tongs. With a little experience it is easy to distinguish a forged from a rolled bar; the rolled bar is smooth and uniform throughout its length, showing faint longitudinal lines due to the rolls, while a forged bar shows the marks of the forging. Usually also there is a difference towards the centre, owing to the centre of the bar having been heated a second time after it has been finished to size. Formerly the old tilt hammer was used for forging, but this has now been almost entirely superseded by small steam hammers.

Temper of Cast Steel.—It has already been pointed out that the “temper” of steel depends, assuming it to have been made from high class material and with proper care, upon its content of Carbon. The particular percentage for any special purpose can only be determined by large experience, and as pointed out by Henry Seebohm,* in his paper before the

* *Iron and Steel Inst. Journ.*, 1884, vol. ii.

Iron and Steel Institute on crucible steel, in all cases, where this high-class steel is required, it is greatly to the interest of the user to explain fully his requirements to the manufacturer when ordering, instead of ordering a steel with a certain percentage of Carbon. For the more common purposes for which crucible steel is used, Seebohm recommends steels of the following composition, and his remarks on special properties of different Carbon steels are so to the point that it will be better to quote his exact words:—

“*Razor Temper* ($1\frac{1}{2}$ per cent. Carbon).—This steel is so easily burnt by being over-heated that it can only be placed in the hands of very skilful workmen. When properly heated, it will do twice the work of ordinary tool steel for turning chilled rolls, &c.

“*Saw-file Temper* ($1\frac{3}{8}$ per cent. Carbon).—This steel requires careful treatment; and although it will stand more fire than razor steel, should not be heated above a cherry-red.

“*Tool Temper* ($1\frac{1}{4}$ per cent. Carbon).—The most useful temper for turning tools, drills, and planing-machine tools in the hands of ordinary workmen. It is possible to weld cast steel of this temper, but only with the greatest care and skill.

“*Spindle Temper* ($1\frac{1}{8}$ per cent. Carbon).—A very useful temper for circular cutters, very large turning tools, taps, screwing dies, &c. This temper requires considerable care in welding.

“*Chisel Temper* (1 per cent. Carbon).—An extremely useful temper, combining as it does great toughness in the unhardened state, with the capacity of hardening at a low heat. It is consequently well adapted for tools when the unhardened part is required to stand the blow of a hammer without sniping, where a hard cutting edge is required, such as cold chisels, hot sets, &c.

“*Sett Temper* ($\frac{7}{8}$ per cent. Carbon).—This temper is adapted for tools where the chief punishment is on the unhardened part, such as cold sets, which have to stand the blows of a very heavy hammer.

“*Die Temper* ($\frac{3}{4}$ per cent. Carbon).—The most suitable temper for tools where the surface only is required to be hard, and where the capacity to withstand great pressure is of importance, such as stamping or pressing dies, boiler cups, &c. Both the last two tempers may be easily welded by a mechanic accustomed to weld cast steel.”

Chemistry of the Process.—The chemical reactions which take place during the melting of crucible steel will vary from oxidising to reducing, according to the mixture of materials charged and the crucibles used. In cases where rusty scrap iron and Oxide of Manganese are used in clay crucibles, at first a more or less oxidising slag will be formed, but as the steel gets completely melted the Oxide in the slag will be gradually more and more reduced by the Carbon present, and its oxidising action therefore becomes less and less energetic, and finally, during the “killing” of the steel, the reducing conditions so predominate, that not only iron, but even Silica, is reduced from the slag and crucible walls, and passes into the metal. This, in all probability, is the explanation of “killing,” as we know in the case of mild steel that the addition of small quantities of Silicon has a very marked effect in producing soundness. In 1861, Sir Henry Bessemer showed that very small additions of Silicon had a remarkable effect in producing solid ingots, and, according to the experiments of Turner,* the addition of 0.02 per cent. of Silicon was sufficient to make “lively” Bessemer basic metal quiet in the moulds, and give solid ingots. When Plumbago crucibles are used the reduction of Silicon from the crucible is much more marked, and Howe† gives analyses showing that as much as 0.6 per cent. of Silicon, in

* *J. Chem. Soc.*, vol. li., p. 136.

† Howe, *Metallurgy of Steel*, p. 313.

some cases, is reduced, and passes into the metal during melting, and the addition of carbonaceous material to the charge tends to produce the same result, although to a less extent. Under ordinary conditions of work with clay crucibles, it is only with the greatest difficulty that steel, containing less than 0.1 per cent. of Silicon, can be obtained, even when the purest material is used. The addition of Ferro-Manganese, probably partly by increasing Carbon content, tends to increase the amount of Silicon reduced, whilst Oxide of Manganese, or any other oxidising agent, has the reverse effect. High temperature and length of "killing" also favour the reduction of Silicon, other things being the same. There is no elimination of Phosphorus, but, in fact, a slight relative increase, and Sulphur also slightly increases, being taken up, to a small extent, from the furnace gases.

Very low Silicon steel can be made by the addition of small quantities of Aluminium shortly before teeming, as this seems to have the same effect in quieting the steel as Silicon, and enables "killing" to be dispensed with, so that practically very little Silicon is reduced, and passes into the steel. Great care must be taken not to add too much Aluminium, .02 to .03 per cent. being all that is required. The use of Aluminium is now becoming very general in crucible steel manufacture as a substitute for killing.

Gas-fired Crucible Furnaces.—Numerous attempts have been made from time to time to introduce gas regenerative furnaces for crucible steel making, but notwithstanding that great economy of fuel is effected they have not been generally adopted. Various reasons have been given for this, but the principal objection appears to be that it is difficult to heat the entire crucible to the same temperature, the bottoms being always somewhat cold, and consequently that equable casting temperature so essential to the production of the highest class of crucible steel is not regularly obtained. A furnace designed by Messrs. Dawson, Robinson & Pope especially to meet this difficulty is shown in fig. 188, and is giving excellent results at the works of Messrs. Jessop & Sons, Sheffield. The gas and air ports in this furnace are lower than the bottom of the crucible, and it is especially designed so that all the separate holes containing the pots or crucibles may be kept at an even temperature. The saving in fuel is said to be at least £2 10s. on every ton of steel made, only 1½ tons of slack being used as against 3 tons of high-class coke in ordinary "coke-hole" practice.

The pot holes are arranged to hold six crucibles, and three such holes are connected with one set of regenerators—*i.e.*, two gas and two air regenerators, as shown in the sketch. The pot holes are sunk below the floor level in the usual way, and each has four ports connected with the regenerators—two with the air and two with the gas—so that gas and air enter through two and meet at the entrance to the pot hole at the bottom, where combustion takes place. The flame travels in a horse-shoe direction round the crucible, and the products of combustion pass down the other ports, heating up the other pair of regenerators. In the sketch (fig. 188) air and gas respectively are shown to be entering by the six ports, *a, a, a,* and *b, b, b,* from regenerators A and B, and the products of combustion to be passing down ports *c, c, c,* and *d, d, d,* to heat up regenerators C and D. The three pot holes form one furnace, and one gas and one air valve reverse the direction of the flame in all three holes. The position of the chimney is arranged to suit local circumstances, and any form of reversing valve similar to those used in ordinary Siemens furnaces may be employed.

Another gas-fired crucible furnace is the "New Form Siemens," which,

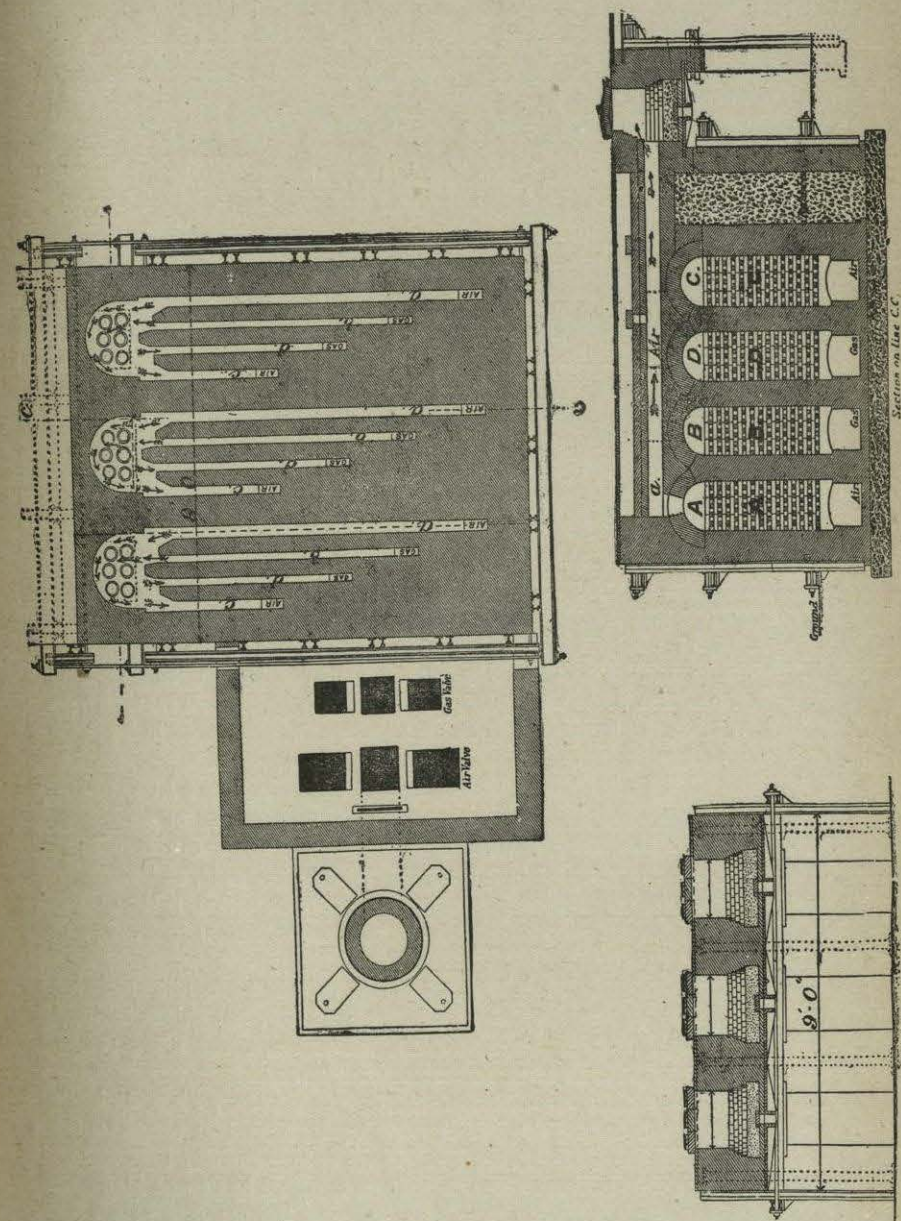


Fig. 188.—The Dawson, Robinson & Pope Gas Crucible Steel Furnace.

The air and gas respectively are entering by the six ports, *a, a, a,* and *b, b, b,* from the air regenerator, A, and gas regenerator, B, and products of combustion are passing down ports *c, c, c,* and *d, d, d,* heating up regenerators C and D.

as applied to open hearth work, is described in Volume II. The crucible furnace differs, of course, from the open hearth "New Form" in constructional details, but it embodies the same general principles, and thus realises similar advantages.

This furnace (figs. 189, 190, and 191) has given excellent results at Sheffield and elsewhere. A six-pot furnace has been erected at Sheffield University, and I am informed that it is in every way satisfactory, and that there is not the least trouble with cold bottoms to the crucibles. Furnaces of his newest design with twelve pots are stated by Mr. Frederick Siemens to be giving equally good results at steel works both in this and other respects.

The fuel consumption is said to vary from 19 to 25 cwts. of slack or nut coal, according to the quality of the coal used and the class of steel required, and this is equivalent to a saving of from £2 10s. to £3 per ton, taking English prices for coal and coke. The pots also last a greater number of heats, and at one Sheffield works are said to be used four and sometimes five times, against three times in the ordinary coke-hole, and the furnace itself is stated to have worked for 18 months without stopping for repairs. Mr. Frederick Siemens informs me that at one works in Germany the total saving in pots and fuel amounted to £4 12s. 3d. per ton of steel produced. This saving will vary with the relative prices of coke and coal and refractory materials in different districts, but must in any case be considerable.

The economy in fuel, ease with which gas can be regulated, freedom from clinker on pots—which should lead to considerable economy in this direction—offer so many advantages over the coke hole that, notwithstanding past failures of gas furnaces, there seems every prospect of gas-fired furnaces being very largely adopted in crucible steel melting. In the States gas furnaces are used almost exclusively. Mr. R. A. Hadfield, writing in the *Iron and Coal Trades Review*, 1895, stated that in Pittsburg they were melting by natural gas with one-fourth to one-fifth the amount of fuel used in "pot" furnaces in England.

Taking the weekly production of crucible steel in Sheffield at 1,000 tons, each ton requires about 3 tons of coke, equal to 150,000 tons of coke per annum, costing £112,000 to £180,000, at 15s. to 25s. per ton. Furnaces run in America by producer gas do not use more than 15 to 20 cwts. of "slack" per ton of crucible steel melted, costing 6s. to 8s. per ton, which, if the same were done at Sheffield, would mean a saving of from £100,000 to £120,000 per annum.

Howe* gives the cost of fuel for producer gas melting crucible steel as about 90 cents per ton, as against 50s. to 60s. at Sheffield, but this is taking slack at about 85 cents per ton of 2,000 lbs., which is a much lower price than that at which good slack can be obtained in England.

Where crucible steel is used for large castings the ordinary Siemens furnaces with a flat hearth seem to give excellent results, and at the Krupp Works are almost, if not entirely, used for crucible steel melting; but the conditions are somewhat different to those when the steel has to be teemed into small cast-iron moulds, and any slight variation in temperature between the top and bottom of the crucible is undoubtedly of more importance in the latter case.

* Howe, *Metallurgy of Steel*, p. 310.

Sier

PLATE XVd.—“New Form Siemens” Steel Furnace.

[To face p. 260.]

The gas made in the gas producers, *a, a*, passes into the main gas flue, *c*, in which are the gas valves, *d*. According to the position of these valves the gas passes along one or other of the gas flues, *g*, to the port, *i*. The air enters the air valve, *e*, passes along one or other of the flues, *h*, through one of the regenerators, *f, f'*, and thence to the port, *i*. The products of combustion pass in the reverse direction to the air, and so reach the chimney flue, *m*. *A* is a damper by means of which any gas producer may be shut off for repairs or when less gas is required. *L* is a hole communicating between the air flue and the gas port, so that a small flame of air burns in the gas and further heats it before it reaches the furnace and is completely burnt in its passage along the bed, *b*.

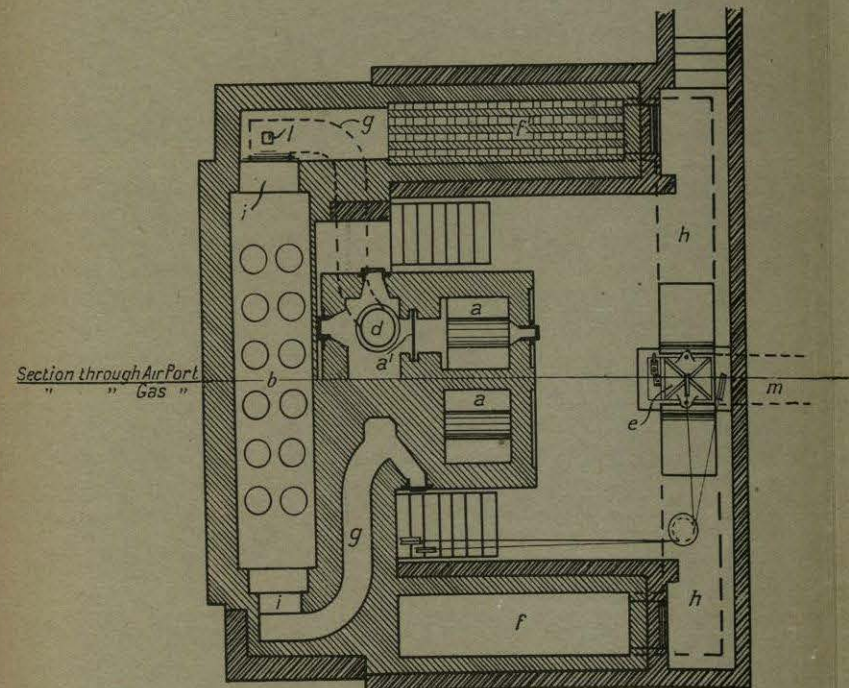


Fig. 189.

Red Brick ---
Fire Brick ---

Fig. 190.

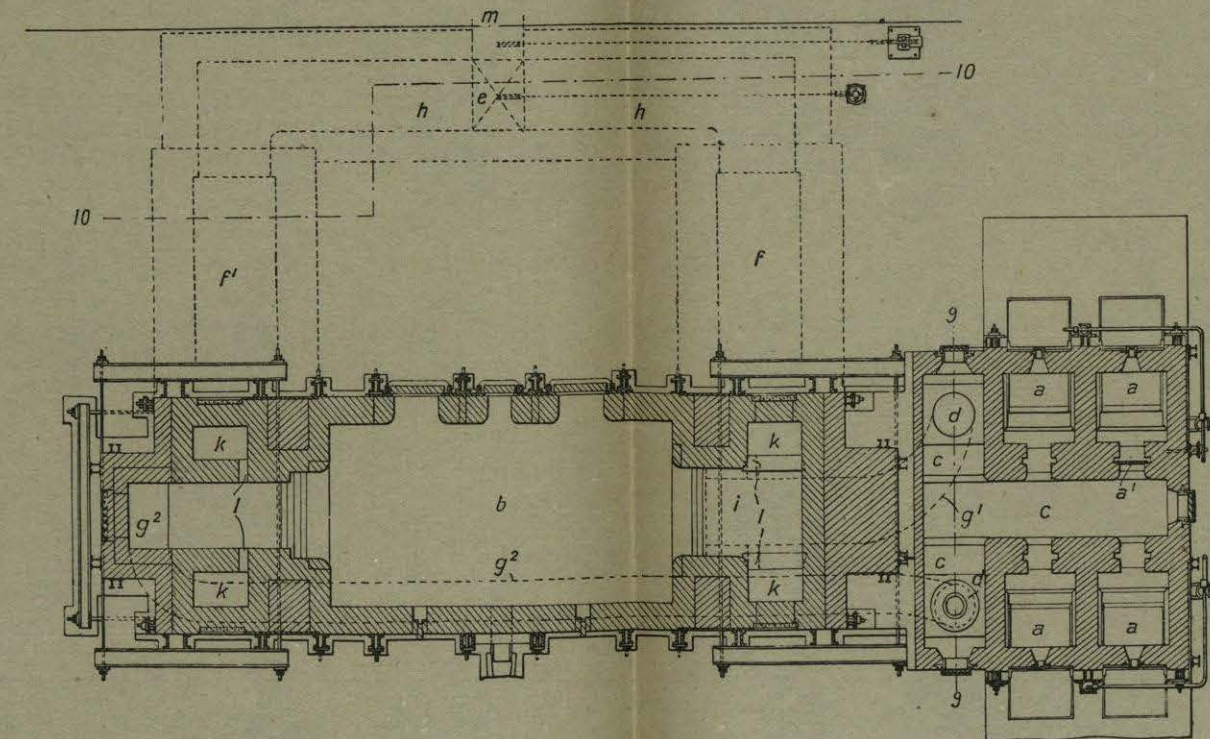
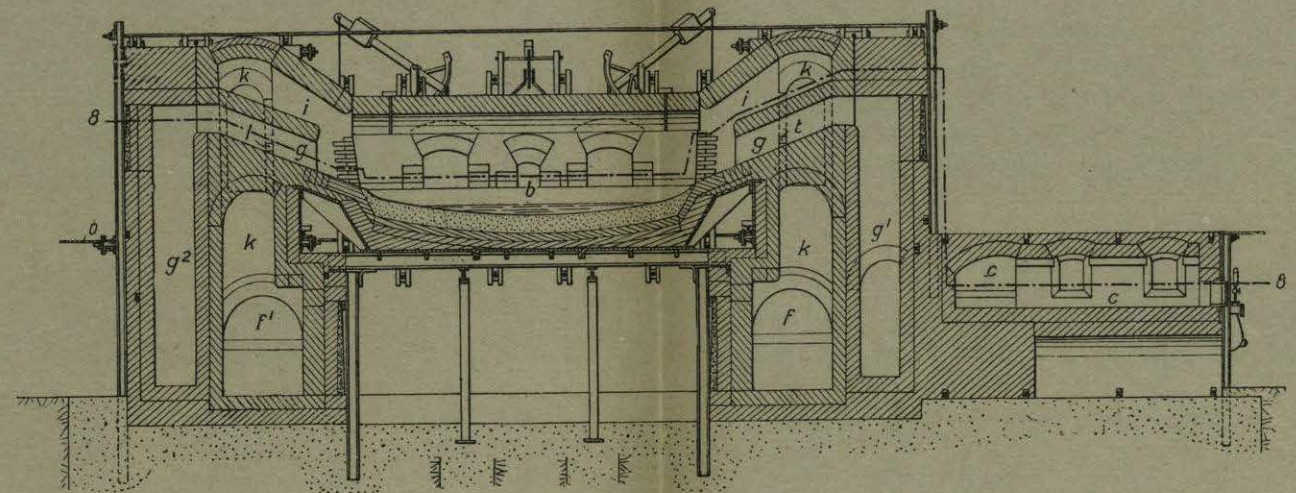


Fig. 191.