lead electrode, and not on the extent of surface offered by those alloy contained much or little tin, since it depends on the difference of potential between the tin sheetlets in the alloy and the sheetlets. And such is the electromotive-force curve of these alloys found by Laurie (Fig. 58).*

CHAPTER VIII. — THE METALLOGRAPHY OF IRON AND STEEL

138. Introduction. — Let us first survey in a general way the different classes of iron and steel, their constitution, and their properties. Let us next consider the genesis of that constitution, and in Chapter IX the correspondence between the changes in that constitution, *i. e.,* the transformation in the solid metal, and the prominent methods of heat-treatment.

139. General Survey. — What are the iron and steel of commerce and industry? Examined under the microscope they prove to be composite or granitic substances, intimate mechanical mixtures or conglomerates of microscopic particles of certain quite distinct, well defined, simple substances, in widely varying proportions. The structure of these conglomerates is of the type shown in Fig. 1, p. 3.

The chief of these substances are,

(1) pure (or nearly pure) metallic iron called *ferrite,* soft, weak, very ductile, with high electric conductivity, and in general like *copper* in its qualities, color excepted,

(2) a definite iron carbide, Fe_3C, called *cementite,* which is harder than *glass* and nearly as brittle, but probably very strong under gradually and axially applied stress.

* We may regard these alloys as mixtures not of chemically pure lead and tin, but of sheets of slightly plumbiferous tin and of slightly stanniferous lead. From the drop of electromotive force as we pass from pure tin to tin containing one per cent of lead, and the substantial horizontality of the curve to the right of this (for the deviation appears to be well within the limits of experimental error), it appears that one per cent (or perhaps even less) of lead suffices to saturate tin; so that the composition and hence electromotive force of the sheetlets of tin is independent of the total quantity of lead present provided this reaches one per cent, or the perhaps smaller quantity needed to saturate the tin.

Take immediately as the most important fact, the most essential part of the skeleton about which the various phenomena are to be grouped, that the great classes of iron and steel of chief value to the engineer and probably to the world at large, are essentially intimate mixtures or conglomerates of these two strikingly different microscopic constituents, ferrite extremely soft and ductile, cementite extremely hard and brittle, the former like copper, the latter like glass. The properties of several of the classes may indeed be influenced, and very profoundly, by thermal and mechanical treatment, and by the presence in certain of them of slag or of graphite; but the fact on which our attention should be concentrated at first is this, that the difference in properties between the different industrial classes of iron and steel are due chiefly to differences in the ratio which the ferrite bears to the cementite.

What has just been said does not apply, it is true, to what is called "hardened steel," which consists not of ferrite and cementite but essentially of austenite, as will be explained shortly; but it does apply to the great industrial classes of wrought iron and of steel such as ship, rivet, fencing-wire, tube, rail and tin-plate steel, and indeed all structural steels whether for plates, beams, eye-bars, angle-irons or any like object.

The steels which are especially soft and ductile, *e. g.,* the rivet and boiler-plate steels, consist chiefly of the soft, ductile, copper-like ferrite, as do those with very high electric conductivity, such as telegraph and telephone wires. In these steels the proportion of cementite may not exceed one per cent of the whole, the rest consisting almost wholly of ferrite.

The harder steels like rail steels, which are called upon to resist abrasion, *e. g.,* the grinding action of the car-wheels intensified by the presence of sand between wheel and rail, have a much larger proportion of cementite. About 93 per cent of their total mass is made up of ferrite and the remaining 7 per cent consists of cementite. This quantity of cementite suffices to increase greatly the resistance to abrasion, while the loss of ductility which it causes, though very marked, is not dangerously great.

Naturally, as the proportion of cementite in steel increases and that of ferrite decreases, the ductility diminishes continuously and the hardness increases continuously; the tensile strength.

however, reaches a maximum when the cementite amounts to about 15 per cent of the whole, and the ferrite is about 85 per cent; with further increase of cementite the tensile strength again decreases. These facts are sketched roughly in Fig. 59. The lines in this figure are intended only to give a sort of bird's-eye view of the subject, because, for given constitution, the properties vary very greatly with the treatment which the metal has undergone. Indeed, in case of hardness trustworthy quantitative data are not at hand.

The constitution of steel is not in general reported in the percentages of ferrite and cementite; nor, indeed, are most engi-

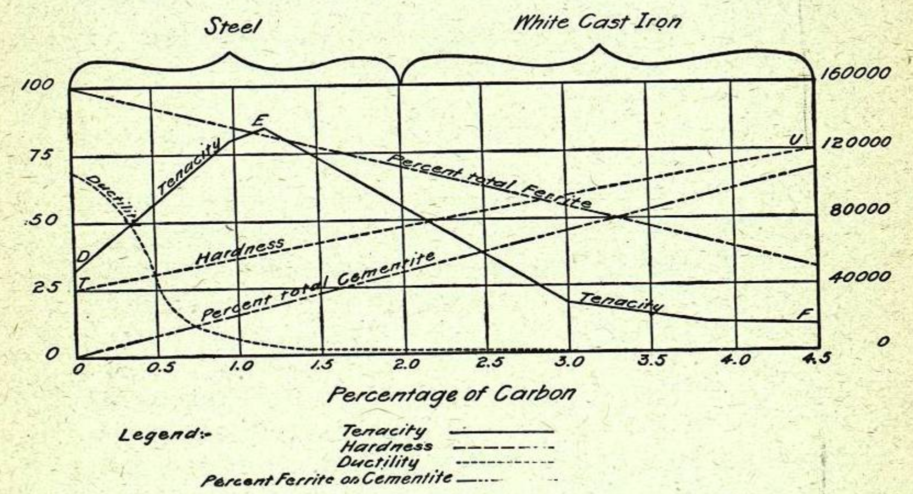

Fig. 59. Physical Properties and Assumed Microscopic Constitution of the Pearlite Series, Graphiteless Steel Slowly Cooled, and White Cast Iron.

NOTE.—By "Total Ferrite" is meant both that which forms part of the pearlite and that which is in excess of the pearlite, taken jointly. So with the "Total Cementite."

neers and metallurgists of to-day sufficiently familiar with this aspect of the subject to speak of it with confidence. But this is the aspect which the practitioners of the near future must face, and it is also that which enables us to understand the relation between the composition and properties of these different classes of iron and steel. Instead of saying that a certain kind of steel, for instance rail steel, contains so much cementite and so much ferrite, it is customary to report simply the carbon which that

cementite represents. For instance, instead of saying that rail steel contains about 7.5 per cent of cementite and nearly 92.5 of ferrite, we habitually and for convenience say that it contains about 0.50 per cent of carbon, which is the quantity represented by the presence of 7.50 per cent of cementite. (For the calculation on which this statement is based see § 153, p. 182.)

Besides these two constituents of prime importance, ferrite and cementite, there are three others of moment; these are graphite, slag, and austenite.

Graphite: Gray Cast Iron.—Graphite is an important constituent of cast iron, especially of gray cast iron, but for our present purpose we may regard it as either absent from steel or, if present, only in unimportant quantities.

Gray cast iron, the only kind of cast iron which can be widely used by engineers, may be regarded as a conglomerate of the second degree; for it consists first of a mechanical mixture of ferrite with cementite quite as steel does; while through this mixture as a matrix* there is scattered much free carbon in the form of sheets of graphite as shown in Fig. 60, p. 164. A weak, foreign body like graphite of course both weakens and embrittles the mass taken as a whole; hence the weakness and brittleness even of gray cast iron.

The graphite itself is pure or very nearly pure carbon in very thin, flexible sheets, which form a more or less continuous skeleton running through the mass of gray cast iron. It appears to be identical with the native mineral graphite (black lead, plumbago).

White cast iron typically would consist of cementite and ferrite quite as structural steel does, but with a much larger proportion of cementite, rising even to 67 per cent (say 4.50 per cent of carbon). Hence the extreme hardness and brittleness of this class of cast iron, so extreme as to exclude it from most engineering uses. But most of the white cast iron of commerce has a constitution intermediate between this extreme type on one hand and gray cast iron on the other; it contains much more cementite than gray cast iron and much less graphite. It is then, like gray cast iron, a conglomerate of the second degree, consisting first of a metallic matrix which is itself a conglomerate

* For meaning of "matrix" as here used see Appendix, § 327.

of much cementite with a variable proportion of ferrite, and second of a small quantity of graphite interspersed through this matrix.

Slag: Wrought Iron. — Wrought iron consists essentially of a metallic matrix identical with low-carbon steel, in which is mechanically mixed a small quantity of slag, a silicate of iron; this slag is not unimportant, yet it is far less important than the ferrite and cementite of the matrix.

Austenite: Hardened Steel. — Steel hardened by sudden cooling from a red heat consists essentially of austenite, a solid solution of carbon in iron of varying degrees of concentration (see

Fig. 60. Gray Cast Iron, cast in sand. Silicon, 1.54 per cent; Sulphur, 0.075 per cent (Sauveur, *The Metallographist*, III, p. 156).

§ 149, p. 179). When austenite contains as much as one per cent of carbon it is intensely hard and brittle; and indeed its hardness and brittleness are roughly proportional to the quantity of carbon which it contains. Hence steels for purposes which require extreme hardness, such as files and other tools for cutting metals and even wood, have from about 0.75 to 2.00 per cent of carbon, enough to give the degree of hardness required for the special purpose, but not enough to cause a prohibitory degree of brittleness; and they are "hardened" by sudden cooling.

Besides the cutting tools, armor-plate and projectiles are habitually made of hardened steel, and therefore consist essen-

tially of austenite. Thus the austenitiferous steels are of importance, at least when contrasted with the non-ferrous metals; but the quantity of austenitiferous steel in actual use is but an insignificant fraction of the non-austenitiferous, that which consists essentially of ferrite and cementite.

On a general diagram or map of the iron-carbon compounds, such as Fig. 68, p. 194, each of these constituents has its normal or indigenous region, with limits of carbon-content east and west, and limits of temperature north and south. Certain of these limits are as yet imperfectly established, and indeed for certain of these territories the normal constituents have not been determined with certainty. Further, these constituents are somewhat vagrant, and often stray far beyond their indigenous region, or rather their theoretical habitat. Nevertheless, this map, which we owe chiefly to Roberts-Austen, Osmond and Roozeboom, aids indispensably in studying this whole question. No student can be said to have a good understanding of iron metallurgy who has not mastered its general outlines.

Table 7, p. 186, gives an approximate idea of the constitution of these various classes of iron and steel.

Heat-treatment. — As has been mentioned in passing, the properties of certain classes of iron and steel are influenced very greatly by thermal treatment. While this appears to act (1) in part by changing the size and arrangement of the microscopic crystalline grains of which the conglomerate mass consists, and probably (2) in part by inducing allotropic changes in the iron proper, yet (3) a very large part of its influence is through shifting the condition of the carbon between the three states of cementite or iron carbide (Fe_3C), austenite or solid solution of carbon in iron, and free carbon or graphite. In view of this latter mode in which heat-treatment affects the properties of the metal, it is but natural that its influence should in general be the more pronounced the more carbon the metal contains. Thus wrought iron and the very low-carbon steels containing from 0.06 to 0.10 per cent of carbon are in general but little affected by heat-treatment; while the high-carbon steels are influenced most strikingly. Cast iron, too, may be affected very greatly by heat-treatment.

Alloy steels, such as nickel, manganese, tungsten, chrome and molybdenum steel, have important specific qualities which collectively are of importance; but their importance is secondary to that of the great classes which have already been outlined.

To recapitulate, the essential distinction between wrought iron and steel is that the former necessarily contains a small quantity of slag, which the latter lacks. The great and striking distinction between steel and cast iron is that the former contains less carbon than the latter; the boundary between them may be put roughly at two per cent of carbon.

Having thus taken a sort of bird's-eye view of the subject, we may now take up some of the special points in much greater detail.

TABLE 4. — *General Classification of Iron and Steel.*

		With Very Little Carbon	With a Moderate Amount of Carbon	With Much Carbon
Slag-bearing or Weld-metal Series		WROUGHT IRON PUDDLED IRON; BLOOMARY OR CHARCOAL IRON	*Weld Steel* *Puddled Steel*; *Blister Steel*	
Slagless or Ingot-metal Series			MALLEABLE CAST IRON	
Slagless or Ingot-metal Series	Normal or Carbon Group	*Soft Steel or Ingot Iron* *Bessemer* *Open Hearth* *Crucible (Mitis)*	*Half-hard and Hard Normal or Carbon Steel* *Bessemer* *Open Hearth* *Crucible*	NORMAL CAST IRON WHITE, MOTTLED, GRAY, SILVERY, WASHED-METAL
Slagless or Ingot-metal Series	Alloy Group		*Alloy Steels* *Nickel Steel*; *Tungsten Steel* *Manganese Steel*; *Chrome Steel* *Silicon Steel*	ALLOY CAST IRONS FERRO-TUNGSTEN FERRO-MANGANESE FERRO-CHROME FERRO-SILICON SILICO-SPIEGEL
Per Cent Carbon		0 to 0.3	0.3 to 2.0	2.0 to 4.5 | to 6.0

NOTE. — In order to make this table clearer, a special type is used for each of the three great classes, wrought iron, steel and cast iron. The wrought iron is given in Roman capitals, all the different varieties of steel in Italics, and all the different varieties of cast iron in Roman small capitals.

140. GENERAL CLASSIFICATION OF IRON AND STEEL. — Table 4 shows the different important varieties of iron and steel. They may be divided (1) according to the presence or absence of slag into (A) the slag-bearing or weld-metal and (B) the slagless or ingot-metal series; (2) according to their carbon-content into (A) low-carbon steel and wrought iron, (B) higher carbon steel and (C) cast iron; (3) according to whether their properties are due chiefly to their carbon or to some other element, into (A) the normal or carbon and (B) the alloy steels and cast irons; and (4) according to the method of manufacture, into (A) Bessemer, (B) open-hearth steel, *etc.*

Of these four bases of classification the second, carbon-content, is decidedly the most important.

141. DIVISION INTO THREE GREAT CLASSES ACCORDING TO CARBON-CONTENT. — Thus divided there are three great classes, which are as follows:

(1) with less than 0.30 per cent of carbon, called *soft* or *low-carbon steel* when free from slag, and *wrought iron* when containing slag; soft, ductile and relatively weak (tensile strength say 50,000 to 80,000 pounds per square inch in case of steel), *i.e.*, weaker than the second class, higher carbon steels, yet far stronger than cast irons, and with relatively little hardening power. (§ 139, p. 164),

(2) with between 0.30 per cent and 2.00 per cent of carbon, called *medium* and *high-carbon,* or *half-hard* and *hard steels,* harder, less ductile, and stronger than the low-carbon steels, more ductile and far stronger than the cast irons, and with marked hardening power. The tensile strength generally lies between say 80,000 and 130,000 pounds per square inch. The hardness and hardening power increase, and the ductility diminishes as the carbon increases, in each case apparently without limit; while the tensile strength increases with the carbon-content till this reaches about 1.00 or 1.20 per cent, and then again decreases,

(3) with more than 2.00 per cent of carbon, called *cast iron,* which is much weaker and much less ductile than classes (1) and (2). Cast iron may be either "white," "gray" or "mottled."

In *white cast iron* most of the carbon is chemically combined with the iron instead of being in the state of graphite.

Gray cast iron contains much of its carbon in the condition of graphite, so that the cast iron itself is a conglomerate of this free or graphitic carbon mechanically mixed with the remainder or metallic part of the mass, which may be called the "matrix."

Mottled cast iron is intermediate in composition between gray and white cast iron, having part of its carbon free or graphitic, and the rest chemically combined with the iron.

Of these three kinds of cast iron, the gray is by far the softest and least brittle, the white is the hardest and most brittle, while the strongest cast iron is between the extremes of the grayest and the whitest.

Gray cast iron may be as soft as the low-carbon steels, and white cast iron may be as hard and perhaps harder than any even of the high-carbon steels; but all these cast irons are both weaker and more brittle than either low or high-carbon steel. Thus all cast irons are weak and brittle, but some are very soft and others very hard.

Fig. 59, p. 162, shows in a general way these three important physical properties, the strength, ductility, and hardness of these three classes of iron (for the moment leaving gray and mottled cast iron out of sight), and how these properties are related to the carbon-content. The whole may be summed up by saying that as the carbon increases, the hardness increases and the ductility decreases, both without limit; but that the tensile strength reaches a maximum with about 1.00 or 1.20 per cent of carbon, and decreases with farther increase of carbon.

Wrought Iron. — The members of the weld-metal class contain a small quantity (usually from 0.20 to 2.00 per cent) of slag or cinder, (in this case a very basic silicate of iron oxide), because they are made by welding together pasty particles of metal at a very high temperature, in a bath of this slag, without subsequent fusion or other means of expelling it completely. Of this series the only member today of importance is wrought iron, which usually contains only a very little carbon. Its characteristic structure is shown in Fig. 61, in which the black streaks are little rods of slag drawn out in the process of rolling or hammering the balls, in which the wrought iron is first made, into bars or sheets. The remainder of the mass is essentially made up of separate crystals of nearly pure iron or "ferrite," interfering with each other and hence misshapen. The differences in tint are due

to differences in the way in which different crystals are acted upon by the nitric acid or other reagent with which the specimen is etched, differences which in turn are due to such causes as difference in orientation, *i. e.*, in the direction of the axes and cleavage of the different crystals.

Wrought iron differs from the low-carbon steels, *e. g.*, from those used for making rivets, fencing-wire, and the sheet iron used for conversion into tin plate by coating with tin, essentially in containing this small quantity of slag. Such steel is practically

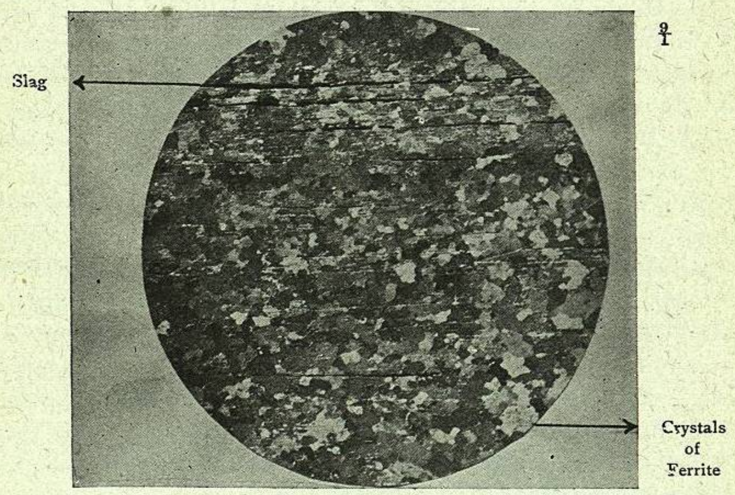

Fig. 61. Wrought Iron Forged. Longitudinal Section.

With the exception of the rods of slag shown in black, the whole of the mass consists of crystals of ferrite interfering with each other and therefore irregular in shape. (Sorby, *Jour. Iron and Steel Inst.*, I, 1887, p. 255, *et seq.*)

free from slag, for the simple reason that it is cast in a very fluid state into ingots or other castings, and that this fluidity enables any slag present to separate by rising to the surface by gravity. The carbon-content of wrought iron and of such steel is substantially the same, and hence their properties are closely alike, save in so far as those of wrought iron are affected by the presence of this small quantity of slag. As such steel is actually made, it usually contains rather more manganese but less phosphorus than most wrought iron; this gives a slight further difference in