

properties between most wrought iron and most of such steel; but this difference is neither necessary nor essential.

142. DEFINITIONS.—In considering the foregoing classification we note that there are two distinct bases for the name steel. The “weld-steels” are called steel because they differ from wrought iron in containing a considerable quantity of carbon, and from cast iron in being malleable; the low-carbon steels are called steel because they differ from wrought iron in being slagless, and from cast iron in being malleable. This confusing nomenclature must be endured, at least for the present.

But the matter is not so serious as it looks at first. The weld steels are unimportant. The three important classes are wrought iron, steel, and cast iron. Wrought iron is readily and almost sharply distinguished from the others by its containing slag. And, fortunately, there is one criterion which we may adopt for discriminating between all the various classes of steel on one hand and those of cast iron on the other, a criterion which we may apply to all future varieties of iron when we seek to decide whether they ought to be called steel or cast iron. This criterion is malleableness in at least some one range of temperature; we may adopt it because such malleableness is probably the only important specific property which all steels of to-day have, and all cast irons of to-day lack, if we except the special product known as “malleable cast iron,” which really stands in a class by itself, through its genesis, constitution and properties. In the following scheme of definitions this criterion is used.

Cast iron, iron containing so much carbon or its equivalent as not to be malleable at any temperature.

In case of the normal or carbon cast irons, which owe their properties chiefly to their carbon-content, as distinguished from the alloy cast irons (see below), the dividing line between steel and cast iron may for the present be put arbitrarily at 2.00 per cent of carbon. As soon as the boundary between the normally graphitiferous and the normally non-graphitiferous varieties of the iron-carbon compounds shall have been determined, it may be well to adopt this natural division line as the boundary between steel and cast iron, instead of the arbitrary boundary which is here used as a temporary expedient. (See § 163, p. 195.)

In gray cast iron a considerable part of the carbon is present as free graphite; in white cast iron there is very little graphite,

most of the carbon being in chemical combination with the iron. In mottled cast iron an intermediate quantity of graphite is present.

Malleable cast iron, iron which when first made is cast in the condition of cast iron, and is made malleable by subsequent treatment without fusion.

Steel, iron which is malleable at least in some one range of temperature, and also is either (a) cast into an initially malleable mass; or (b) is capable of hardening by sudden cooling; or (c) is both so cast and so capable of hardening. (Tungsten steel and certain classes of manganese steel are malleable only when red-hot.)

Alloy steels and *cast irons* are those which owe their properties chiefly to the presence of an element (or elements) other than carbon.

Wrought iron, slag-bearing, malleable iron, which does not harden materially when suddenly cooled. Most wrought iron to-day is “puddled iron,” *i. e.*, made by the puddling process (§ 274, p. 344).

Ingot iron, (rare), slagless steel containing less than 0.30 per cent of carbon.

Ingot steel, (rare), slagless steel containing more than 0.30 per cent of carbon.

Weld iron, (rare), the same as wrought iron.

Weld steel, (rare), slag-bearing varieties of iron malleable at some temperature, and containing more than 0.30 per cent of carbon. It differs from wrought iron only in containing more carbon.

Some additional definitions are given in Appendix 2.

143. CARBON AND IRON.—In our study of the metallography of iron, which occupies the rest of this chapter, we may confine our attention to the slagless or ingot-metal series, and to the normal or carbon group of that series, leaving both the weld-metal series and the alloy steels and alloy cast irons out of consideration. What we are going to consider, then, is a series of quasi-alloys of iron and carbon, called *steel* when they contain less than say 2 per cent of carbon, and *cast iron* when they contain more.

Let me again emphasize the fact that the properties of the metal are profoundly influenced by its carbon-content. The essential difference between the most ductile rivet steel, nearly as

soft and malleable as copper, and the hardest or most springy tool or spring steel, and the hardest and most brittle cast iron, is due to the differences in the quantity and condition of their carbon. Table 5 illustrates this.

TABLE 5.

PERCENTAGE COMPOSITION OF TYPICAL KINDS OF STEEL						STATE IN WHICH USED	
NAME	C	Si	Mn	P	S		
Rolled or Forged Steel	Rivets04 to .10	.05	.65	.04	.06	Slowly cooled or Pearlite series
	Tubes . . .	.06 to .08	.01	.60	.12	.06
	Tires . . .	.6 to .7	.25	.79	.05	.05
	Bridge . . .	.08 to .18	.10	.80	.06	.07
	R. R. Axles	.25 to .40	.04 to .06	.40 to .80	.06	.05	
Amer. Rails	.45 to .70	.10 to .20	.80 to 1.10	.06 to .10	.06 to .10		
Steel Castings	Dynamos . .	.15	.12	.04	—	—	
	Electrical. }	.25	.20	.45 }	.08	.05	
	Harder Castings	.10	.25	.10 }			
		.30 to .50	.35 to .50	.80	.05	.05	
Rolled or Forged Steel	R. R. Car Springs	.75	.35	.85	.07	—	Suddenly cooled or Austenite series
	Cutting Tools	.75 to 1.50	—	—	—	—	
	Files	1. to 1.50	—	—	—	—	

It is most simple to assume that, in molten iron, all carbon is simply dissolved, and all is alike, no matter what may be the condition of that carbon when the metal solidifies; in short, that all molten carbon-iron compounds are similar solutions of carbon in iron or *vice versa*, differing from each other only in the degree of concentration of this solution.

When, however, the iron solidifies, the carbon may either pass into the condition of free carbon, that is to say, graphite; or it may remain dissolved in the now solid iron, as a solid solution to which the name "austenite" is given. When the metal further cools this austenite and graphite may be preserved and found as such in the cold metal, or they may undergo, partly or wholly, a transformation which leaves the carbon as a definite iron carbide, Fe_3C , called *cementite*.

There are thus three distinct conditions in which carbon can exist in solid iron, (1) as free graphite, characteristic of gray cast iron; (2) as a solid solution of carbon in iron, *austenite*, the characteristic of "hardened," *i. e.*, suddenly cooled steel, and chilled cast iron; and (3) as cementite, an iron carbide Fe_3C , characteristic of normal or slowly cooled steel and cast iron. These and the other constituents of iron will be described in § 145, and at the same time the regions in Fig. 68 (p. 194), in which these constituents ought theoretically to be present, will be enumerated. This figure has already been alluded to in the latter part of § 139, p. 165, and it will be described at much greater length in § 162, p. 193.

144. SOURCE OF THE CONFUSION IN OUR NOMENCLATURE. — It may be of interest to expose in passing the way in which much of the confusion in our present nomenclature has arisen, both to show the student from what motives these systems may arise, and also to give warning of the sort of trouble which is likely to arise in case we give names based, not on essential and definitive properties, but on accidental ones which are not definitive, no matter how important they may be.

Until about 1860 there were only three important classes of iron, — wrought iron, steel and cast iron. The essential characteristic of wrought iron was its nearly complete freedom from carbon; that of steel its moderate carbon-content (say between 0.30 and 2 per cent), which, though great enough to confer the property of being rendered very hard by sudden cooling, yet was not so great as to make the metal brittle when cooled slowly; while that of cast iron was a carbon-content so high as to make the metal brittle whether cooled quickly or slowly. This classification was based on carbon-content, or on the properties which it gave. Wrought iron, and certain classes of steel which then were important, necessarily contained much slag or "cinder," because they were made by welding together pasty particles of metal in a bath of slag, without subsequent fusion. But the best class of steel, crucible steel, was freed from slag by fusion in crucibles; hence its name, "cast steel."

Between 1860 and 1870 the Bessemer and open-hearth processes introduced a new class of iron, to-day called "mild" or "low-carbon steel," which lacked the essential property of steel, the hardening power, yet differed from the existing forms of

wrought iron in its freedom from slag, and from cast iron in being very malleable. Logically it was wrought iron, the essence of which was, that it was (1) "iron" as distinguished from steel, and (2) malleable, *i. e.*, capable of being "wrought." This name did not please those interested in the new product, because existing wrought iron was a low-priced material. The only justifiable alternative would have been to assign a wholly new name to the wholly new product; but as steel was associated in the public mind with superiority, it appeared more attractive to appropriate its valuable name. This was done with the excuse that the new product resembled one class of steel — cast steel — in being free from slag; and, after a period of protest, all acquiesced in calling the new product "steel," which is now its firmly established name. The old varieties of wrought iron, steel, cast steel, and cast iron preserve their old names; the new class is called steel by main force. As a result, certain varieties, such as blister steel, are called "steel" solely because they have the hardening power, and others, such as low-carbon steel, solely because they are free from slag. But the former lack the essential quality — slaglessness — which makes the latter steel, and the latter lack the essential quality — the hardening power — which makes the former steel. "Steel" has come gradually to stand rather for excellence than for any specific quality.

These anomalies, however confusing to the general reader, in fact cause no appreciable trouble to important makers or users of iron and steel, beyond forming an occasional side-issue in litigation.

145. THE MICROSCOPIC CONSTITUENTS OF IRON AND STEEL.

— The general features of the constitution of alloys outlined in Chapter I, may be here recapitulated with the aim of applying them specially to iron and steel.

The great advance which has taken place in our knowledge of the constitution of steel and the other varieties of iron has shown that they resemble very closely the igneous and metamorphic rocks, *i. e.*, exactly those which, like the different varieties of iron, have formed from the cooling of molten or at least pasty masses. Just as a granite on close examination is seen to consist of an aggregation of crystalline fragments of mica, quartz, and feldspar, each of which is a definite chemical compound, with definite crystalline form and definite physical properties in general, so the microscope

shows us that a given piece of steel or iron usually consists of extremely minute crystalline particles of two or more substances, each of which is a definite entity, with definite chemical composition and definite physical properties.

But besides the granitic type, certain varieties of iron seem to represent the obsidian type. In this, as in aqueous solutions, the ratios in which the different chemical substances, the silica, lime, *etc.*, exist are not fixed or definite; they vary from case to case, not *per saltum*, as between definite chemical compounds, but by infinitesimal gradations. The different substances present appear to be dissolved, as it were, in each other in a sort of solid solution which has the indefiniteness of composition, the incapacity of being resolved by any magnification of the microscope, and the feeble chemical attraction between the different components, characteristic of a solution.

The schistose structure of rock masses, their columnar or basaltic structure arranged in columns perpendicular to the cooling surface, their "vugs" or cavities lined with specimens of free crystals, their segregation, *etc.*, are reproduced in a most interesting way in metallic masses.

Of these different microscopic entities which constitute the different varieties of iron, only the following here need consideration:

(1) FERRITE, the microscopic particles of nearly and perhaps perfectly pure metallic iron. It is magnetic, very soft and ductile, but relatively weak, with a tensile strength of about 45,000 pounds per square inch. It is of the isometric system. It always forms a very important part of slowly cooled iron and steel in general (excepting the alloy classes).

It is a normal constituent of regions V, VI and IX of Fig. 68.

When much slag is present, as in wrought iron, and is drawn out into fibers by rolling, the mass as a whole is thereby given a certain kind of pseudo-fibrousness; but even here the metallic or ferrite quasi-fibers usually consist of an aggregation of grains, each of which is equiaxed. (See Fig. 61.)

146. (2) CEMENTITE, a definite carbide of iron, Fe_3C , containing 6.67 per cent of carbon, very brittle, harder than hardened steel, scratching glass and feldspar but not quartz, ($H = 6$), and magnetic. The carbon in slowly cooled steel is chiefly or wholly present as cementite, of which there is therefore $(56 \times 3 + 12) \div$

12 = 15 per cent for each per cent of carbon present. In slowly cooled as distinguished from "chilled" cast iron, too, it is probable that all or nearly all of the combined carbon as distinguished from the graphite is present as cementite. It is one of the constituents of pearlite, and is an important constituent of slowly cooled iron and steel in general, of course excepting the varieties which are nearly free from carbon. Its carbon is often spoken of as *cement-carbon*, and is the *carbide-carbon* of Ledebur.

It is a normal constituent of regions VI, VIII and IX of Fig. 68.

147. (3) PEARLITE, a eutectoid or quasi-eutectic (§ 148), consisting of interstratified plates of ferrite and cementite, in the ratio of about six parts by weight of the former to one of the latter, as inferred from its containing about 0.90 per cent of carbon. The exact composition of pearlite is still in dispute, and I adopt this number of 0.90 per cent only provisionally and for the purpose of fixing our ideas.

Slowly cooled steel consists essentially of a conglomerate of this pearlite plus the excess-substance (see § 34, p. 39), which is ferrite if the carbon-content is below 0.90 per cent, but is cementite if it is above 0.90 per cent. Paraphrasing Osmond, steel may be called "eutectoid," "hyper-eutectoid" or "hypo-eutectoid," according to whether it contains just 0.90 per cent of carbon, or more than that or less. (See Fig. 65, p. 185.)

Slowly cooled cast iron probably consists essentially of a conglomerate (1) of pearlite with its accompanying excess of either ferrite or cementite according to whether the combined carbon is less or greater than 0.90 per cent, and (2) of graphite.

Pearlite is formed by the spontaneous decomposition of austenite, *e. g.*, in cooling past the transformation-point, Ar_1 , *PSP'*, Fig. 68.

It is a normal constituent of regions VI and IX of Fig. 68.

Fig. 62 shows the structure of pearlite. The black stripes are the ferrite, which, although itself white, here looks black simply because it is so much softer than the cementite that in polishing it is ploughed into deep furrows, which, because they are in the shadow of their own walls, look black.

148. EUTECTOID. — Pearlite is a "eutectoid" or quasi-eutectic; in other words, the solid-solution alloy of the lowest transformation-point. The eutectoid is to these transformations within

the solid solution, the solid metal, exactly what the eutectic is to the freezing of a molten solution, a molten eutectiferous alloy. These transformations may be selective, exactly as the freezing is selective, and as they progress the solid mother-metal, in this case austenite, progressively approaches the eutectoid or pearlite ratio of about 0.9 per cent of carbon, exactly as the mother-metal of a freezing alloy progressively approaches the eutectic composition.

As with a eutectic so with a eutectoid, its most striking properties are:

(1) that for any given solid solution its composition and hence its transformation temperature are constant, no matter

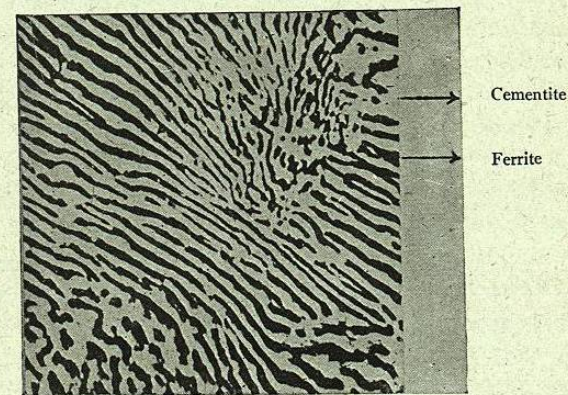


Fig. 62. Pearlite. Steel (carbon about 1 per cent) forged and annealed at 800° C. (F. Osmond, *Baumaterialienkunde*, II, p. 53, *et seq.*, Fig. 17.)

what the initial ratio of the constituent substances is (in the present case the ratio of iron to carbon),

(2) that its composition is not, save occasionally and as it were by accident, in simple atomic proportions (see footnote to §149), and

(3) that it consists of a conglomerate of distinct particles mechanically mixed.

149. (4) AUSTENITE, and the transition forms MARTENSITE, TROOSTITE, and SORBITE, may here be considered together.

AUSTENITE,* a solid solution of carbon (or perhaps of an

*"L'austenite, au contraire, que l'on a des raisons de considérer.

iron carbide), in gamma allotropic iron, is hard and brittle when cold, is normal and hence stable at temperatures above the critical temperature A_3 , *i. e.*, in regions II, IV and VII of Fig. 68, and is slowly transformed by reaction (9), p. 203, into pearlite with either ferrite or cementite as an excess substance, in cooling across region V or VIII into region VI or IX, in which, as already pointed out, ferrite and cementite are the normal and hence stable forms. When it is of the eutectoid composition, *i. e.*, that of pearlite, 0.90 per cent of carbon, it is sometimes called "hardenite."

Because the transformation takes an appreciable time, and because it is indeed arrested on reaching the common atmospheric temperature, it results that if steel in region IV or VII is cooled very quickly as in the "hardening" process of quenching in water, the transformation has not time to complete itself, and the cold steel, instead of consisting wholly of ferrite and cementite, is by lag preserved in one or more of the successive transition stages of, first, martensite, next, troostite, and third, sorbite. Indeed, part of the austenite itself may be preserved without changing even as far as martensite, for instance when steel containing 1.10 per cent or more of carbon is quenched from above A_3 (SE, Fig. 68), in a freezing mixture.* Here and elsewhere carbon seems to retard the change from austenite towards ferrite and cementite; and manganese and nickel have a like effect, so that even without sudden cooling a very large proportion of gamma iron, the characteristic component of austenite, is probably present in certain manganese and nickel steels when cold, giving them very valuable properties.

The difference between these three transition substances and the difference between them and the three primary substances, austenite, ferrite, and cementite, may be only mechanical and quan-

comme non-magnétique, peut représenter les cristaux mixtes gamma in-tacts." Osmond, "Méthode Générale," *Contribution à l'Étude des Alliages*, p. 325, 1901. He restricts the meaning of austenite to the substance present in the cold steel, speculating that it may be identical with the solid solution in gamma iron which exists in regions IV and VII. In breaking away from his definition and defining austenite as the solid solution which exists in these regions, and assuming provisionally that the substance called austenite, which exists in suddenly cooled high-carbon steel actually is identical with it, I hope to simplify the subject so that a larger class of readers may understand it.

* *Idem*, p. 295.

titative, or it may in addition be essential. It may be only mechanical and quantitative, so that these three substances may be simply mechanical mixtures of the three primary substances, differing first mechanically in the size and mode of admixture of the particles of these primary substances, and second quantitatively in the proportion in which these primary substances are present, just as orange, green, indigo and violet really differ only in containing the three primary colors, red, yellow, and blue, in different proportions. Or, in addition to these mechanical and quantitative differences, which are certainly very important, there may be essential differences, *i. e.*, one or more of the transition substances may necessarily and essentially either contain some other primary substance or lack some one of the three known primary substances. Although there is much evidence to support this latter theory, so that many, myself included, believe that martensite, for instance, and the hardened steel of which it is characteristic, owe their properties in part to the presence of beta allotropic iron, yet the evidence is so far from conclusive, opinions differ so much, and the mechanical theory is so much easier to teach and to work with, and it groups together so well the facts important to the practitioner, that it is here adopted provisionally. (See § 342.)

MARTENSITE, the characteristic condition of hardened steel and probably of chilled cast iron, on this theory represents the arrest of the transformation at an early stage, when enough ferrite and cementite have formed within the austenite to modify greatly the properties of the whole, and therefore it is not a definite stage, but it covers a considerable fraction of the course of transformation, though there are convenient boundaries between it and austenite on one hand and troostite on the other, quite as changes in slope form convenient arbitrary boundaries of a mountain, even though it actually shades off without real break into the adjoining plains. In hyper-eutectoid steel it should be chiefly cementite, in hypo-eutectoid steel chiefly ferrite, which has replaced the initial austenite. Its typical structure, apparently that of the austenite from which it forms,* is that shown in Fig. 64, with well marked needles forming three sides of a triangle,

* By etching steel of 1 per cent of carbon when in region IV, where austenite is the natural constituent, Saniter developed a structure much like that of Fig. 64. *Jour. Iron and Steel Inst.*, 1898, I, p. 209.