and often crossing each other, unlike the layers in pearlite which never cross each other. Though the hardness of both austenite and martensite varies very greatly, not only from specimen to specimen, but even in the same specimen,* when austenite and martensite occur together, the martensite is decidedly the harder of the two.† In general it is the harder the more carbon the steel contains, and the more suddenly it is cooled from above the critical range.

Matensite

Austenite

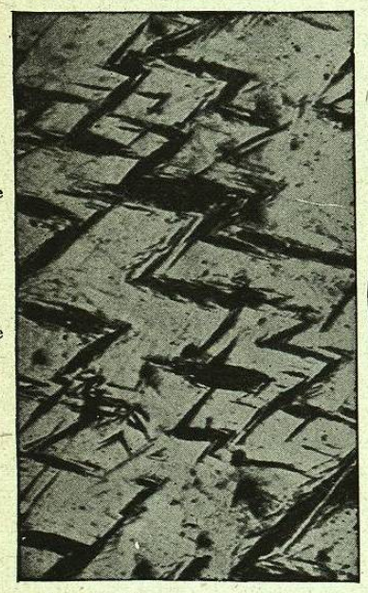

Fig. 63. Martensite (black) in Austenite (white). Steel of about 1.50 per cent Carbon. Quenched at 1,050° C. in ice water. (Osmond, *The Metallographist*, II, p. 261, *et seq.*)

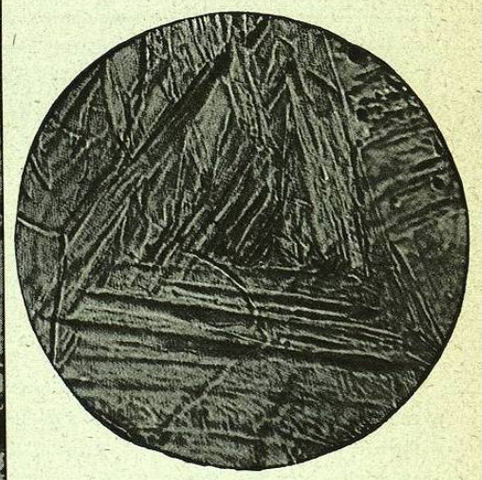

Fig. 64. Martensite. (Osmond and Cartaud, *Annales des Mines*, XIV, p. 62, 1900; *The Metallographist*, IV, p. 236, *et seq.*)

Troostite,‡ the next stage, should contain less austenite, but more ferrite or cementite or both, than martensite. Tempered steel, *i. e.*, steel which has first been brought to the martensite stage by sudden cooling, and has then had its extreme brittleness "tempered" or mitigated by reheating it until its surface

* Kourbatoff, *Revue de Métallurgie*, III, p. 177, 1905.

† Osmond and Stead, *Microscopic Analysis of Metals*, 1904, pp. 170-172.

‡ It has been held, but without just warrant, to be ferrite. Boynton, *Jour. Iron and Steel Inst.*, 1904, I, p. 262.

is coated with a thin skin of iron oxide, probably represents this troostite stage.

Sorbite, the last stage before the completion of the transformation, probably consists chiefly of pearlite with its excess of either ferrite or cementite, perhaps still retaining some residual austenite. But its constituents cannot be detected by the microscope, probably because although the transformation has nearly completed itself, the particles of ferrite and cementite which it has created have not yet succeeded in coalescing into masses large enough to be distinguished.

It is reasonably thought that the excellent quality which can be given by specially managed cooling is due to the very fine division which is the essence of sorbite. Naturally, sorbite shades off without break into troostite on one hand, and through the stage of sorbitic or badly resolved pearlite into that of true pearlite with its excess of ferrite or cementite on the other hand.

The magnetic properties and their relations to these transition stages are briefly discussed in § 336, Appendix 3.

150. (5) Graphite, a characteristic component of "gray cast iron," of which it usually forms from 2.00 to 3.50 per cent. It is pure or nearly pure carbon. When it forms during the solidification of the metal, as is usually the case, it occurs in very thin laminated plates or flakes, often ⅛ inch or more in diameter, and curved as shown in Fig. 60, p. 164. When it forms within the solid metal at temperatures materially below the freezing-point, it occurs, at least under certain conditions, in very fine powder, and is then called "temper" graphite, the temper-carbon of Ledebur.

It is a normal constituent of regions III and VII of Fig. 68. When graphite-bearing iron cools out of region VII into regions VIII and IX, all the graphite theoretically should be transformed into cementite by reaction (10) $Gr + 3Fe = Fe_3C$. (See § 172, p. 200.) But owing to the lagging of this reaction, graphite usually persists and is actually found in the metal in regions VIII and IX.

151. (6) Slag, the characteristic component of wrought iron, which usually contains from 0.20 to 2.00 per cent of it. It is essentially a ferrous silicate, and is present in wrought iron simply because this variety of iron is made by welding together pasty granules of iron in a bath of such slag, without subsequently melting

the resultant mass or in any other way giving the envelopes of slag thus imprisoned a chance to escape completely.

152. (7) THE EUTECTIC formed in the slow freezing of cast iron, *i. e.*, of any iron containing over say 2 per cent of carbon. It contains about 4.30 per cent of carbon, and is a conglomerate of (1) austenite, saturated and hence containing about 2 per cent of carbon, and (2) graphite; so that the eutectic contains about 1.95 per cent of combined or dissolved carbon present in the 97.6 per cent of austenite, and 2.34 per cent of graphite. It is a normal constituent of slowly cooled, *e. g.*, gray cast iron, which may be called hyper- or hypo-eutectic according to whether it contains more or less than 4.30 per cent of carbon, *i. e.*, according to whether graphite or austenite is present in excess over the eutectic ratio.

153. CALCULATION OF THE CONSTITUTION OR PROXIMATE COMPOSITION OF SLOWLY COOLED STEEL AND OTHER STOICHIOMETRIC CALCULATIONS. — We have already seen (§ 148, p. 178) that slowly cooled steel consists essentially of a conglomerate of pearlite together with either ferrite or cementite as the excess-substance, according to whether the percentage of carbon combined with the metallic iron is below (hypo-eutectoid) or above (hyper-eutectoid) the eutectoid ratio of about 0.90 per cent. In the former case the excess-substance is iron or ferrite, in the latter it is carbon or cementite, according to our point of view.

To avoid confusion let us here distinctly recognize that in any hyper-eutectoid steel, for instance one containing 1.00 per cent of carbon, cementite is the excess and iron the deficit-substance, in that there is more carbon but less iron present than corresponds to the eutectoid or pearlite ratio of carbon 0.90, iron 99.10 per cent; and this is perfectly true in spite of the fact that the percentage of iron by weight is ninety-nine times that of the carbon.

As pearlite itself is a conglomerate of ferrite with cementite, so slowly cooled steel whether eutectoid, hypo-eutectoid or hyper-eutectoid, is composed in reality of ferrite and cementite, of which a part is interstratified in the 6:1 ratio as pearlite, and the rest, ferrite or cementite as the case may be, is present as the excess-substance. Such excess is often spoken of as "structurally free" ferrite or cementite.

How much cementite is implied by the presence of 1 per cent of carbon? The presence of 1 per cent of carbon in the mass in the condition of cementite, Fe_3C, implies the presence of

$\frac{3 \times 56 + 12}{12} = 15$ per cent of cementite and of $\frac{3 \times 56}{12} = 14$ per cent of iron in that cementite. Here 12 and 56 are the atomic weights of carbon and iron respectively. Conversely, the presence of 1 per cent of cementite implies the presence of $\frac{1 \times 12}{56 \times 3 + 12} = 0.0667$ per cent of carbon.

How much carbon does cementite contain? The formula of this substance, Fe_3C, shows that it contains $12 \times 100 \div (56 \times 3 + 12) = 6.67$ per cent of carbon.

What is the percentage of ferrite and cementite in pearlite? As pearlite contains about 0.90 per cent of carbon, and as the carbon is present in this pearlite in the form of cementite, so pearlite contains about $0.90 \times 15 = 13.5$ per cent of cementite; and by difference it must contain about $100 - 13.5 = 86.5$ per cent of ferrite, or $86.5 \div 13.5 = 6.4$ parts by weight of ferrite for each part of cementite. To avoid an unjustified air of accuracy, this ratio is called 6:1 in this work.

How much pearlite and how much excess ferrite correspond to a given percentage of carbon in a hypo-eutectoid steel? To fix our ideas let us consider the case of steel containing 0.50 per cent of carbon. We have just seen that this implies the presence of $0.50 \times 15 = 7.50$ per cent of cementite. With this cementite will be associated $7.50 \times 6.4 = 48.0$ per cent of ferrite in the form of pearlite; so that the total quantity of pearlite will be $7.50 + 48.0 = 55.5$ per cent or say 56 per cent.

The remainder of the steel will then be $100 - 55.5 = 44.5$ or say 44 per cent of free ferrite, over and above that contained in the pearlite or in short of "excess ferrite." To sum this up the constitution will be:

Cementite, $0.50 \times 15 =$	7.50
Ferrite associated with it as pearlite, $7.50 \times 6.4 =$	48.00
Total pearlite	55.50
Excess, or free, or "structurally free" ferrite by difference .	44.50
	100.00

In like manner Table 6 and the lines in Fig. 65 have been calculated. In each of these the same principle has been extended so as to cover the graphiteless white cast irons, which really form a prolongation of the hyper-eutectoid steels.

TABLE 6. — *Theoretical Constitution or Microstructural Composition of the Pearlite Series, Slowly Cooled Steel and White Cast Iron, on Sauveur's Plan.*

NAME		CARBON PER CENT	PROXIMATE COMPOSITION PER CENT				
			Pearlite	Excess* Ferrite	Excess* Cementite	Total Ferrite	Total Cementite
Steel	Low-carbon	0	0	100	0	100	0
		0.10	11	89	0	98.5	1.5
		0.20	22	78	0	97.0	3.0
	Medium-carbon	0.30	33	67	0	95.5	4.5
		0.40	44	56	0	94.0	6.0
		0.50	56	44	0	92.5	7.5
		0.60	67	33	0	91.0	9.0
		0.70	78	22	0	89.5	10.5
	High-carbon	0.80	89	11	0	88.0	12.0
		0.90	100	0	0	86.5	13.5
		1.00	98	0	2	85.0	15.0
		1.10	97	0	3	83.5	16.5
		1.20	95	0	5	82.0	18.0
		1.30	93	0	7	80.5	19.5
		1.40	91	0	9	79.0	21.0
		1.50	90	0	10	77.5	22.5
		1.60	88	0	12	76.0	24.0
		1.70	86	0	14	74.5	25.5
		1.80	84	0	16	73.0	27.0
		1.90	83	0	17	71.5	28.5
White Cast Iron		2.00	81	0	19	70.0	30.0
		2.10	79	0	21	68.5	31.5
		2.20	77	0	23	67.0	33.0
		2.30	76	0	24	65.5	34.5
		2.40	74	0	26	64.0	36.0
		2.50	72	0	28	62.5	37.5
		2.75	68	0	32	58.75	41.25
		3.00	64	0	36	55.0	45.0
		3.25	59	0	41	51.25	48.75
		3.50	55	0	45	47.5	52.5
		3.75	51	0	49	43.75	56.25
		4.00	46	0	54	40.0	60.0
		4.50	38	0	62	32.5	67.5

* "Excess Ferrite" means the ferrite in excess over the pearlite ratio, or in other words, the free or structurally free ferrite which does not form part of the pearlite. "Total Ferrite" means the sum of this excess ferrite plus that contained in the pearlite. So, *mutatis mutandis*, with "Excess Cementite" and "Total Cementite."

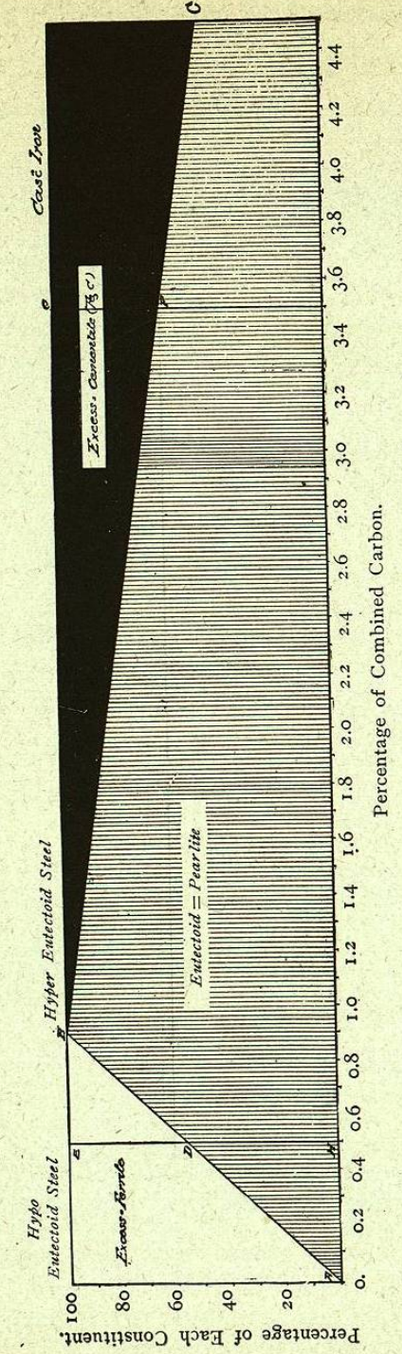

Fig. 65. Constitution of the Iron-carbon Compounds (Sauveur).

The ordinates of *A*, *B*, *C* represent the percentage of pearlite corresponding to each percentage of carbon, and the intercept *E*, *D* or *F*, *G* of any point *D* or *F* measures the percentage of ferrite or cementite for hypo- and hyper-eutectoid steels respectively.

TABLE 7. — *Classification of Iron and Steel by Carbon-content and Microscopic Constitution, Showing the usual Limits.**

TOTAL CARBON PER CENT	UNHARDENED STEEL AND WHITE CAST IRON OR PEARLITE SERIES								GRAY GRAPHITO	
	Name	Prominent Uses	Percentage of Carbon		Microscopic Constitution Per Cent				Name	Prominent Uses
			As Cementite	Graphite	Ferrite	Cementite	Graphite	Slag		
0.05 to 0.3	Wrought Iron		0.05 to 0.3		99.0 to 93.6	0.75 to 4.5		0.2 to 2.0		
	Low-carbon or Mild Steel	Boilers, Ship and Structural Steel	0.05 to 0.3		99.25 to 95.5	0.75 to 4.5				
0.3 to 0.8	Medium-carbon Steel	Axles, Shafting, Tires, Rails	0.3 to 0.8		95.5 to 88.0	4.5 to 12.0	little or none			Lacking
0.8 to 2.00	High-carbon Steel unhardened	Little used	0.8 to 2.00		88.0 to 70.0	12.0 to 30.0	usually little or none			
2.0† to 4.5	White Cast Iron, and Chilled Cast Iron after annealing	Treads of Cast Iron railroad wheels, and other "chilled" castings	1.0 to 4.5	0 to 1.0	84.0 to 32.5	15.0 to 67.5	0.0 to 1.0		Gray and Mottled Cast Iron	Gray iron castings in general (Mottled Cast Iron has few direct uses)

CAST IRON OR PEARLITE SERIES					TYPICAL HARDENED STEEL OR AUSTENITE SERIES				
Carbon in State of		Microscopic Constitution Per Cent			Name	Prominent Uses	Carbon in State of		Microscopic Constitution
Cementite	Graphite	Ferrite	Cementite	Graphite			Cementite	Austenite	
or unimportant					Low-carbon Steel Hardened	Little used			Low-carbon Austenite Chiefly‡
					Medium-carbon Steel hardened (and tempered)	Some springs	0.3 to 0.8 chiefly as Austenite		Medium-carbon Austenite, Chiefly‡
					High-carbon Steel hardened (and tempered)	Cutting tools, springs	0.8 to 2.0 chiefly as Austenite		High-carbon Austenite, Chiefly‡
0.0 to 3.5	1.0 to 4.0	98.0 to 47.0	0.0 to 52.0	1.0 to 4.0	Chilled Cast Iron unannealed		2.0 to 4.5 chiefly as Austenite		Supersaturated Austenite‡ (2 + per cent Carbon) Chiefly

* This table is intended to give only a bird's-eye view or very rough classification. The numerical limits in particular are very rough. This is particularly true of the third or austenite series. Mottled cast iron has few direct uses, except, of course, that it, like gray cast iron, is used for conversion into wrought iron and steel.

† For simplicity the limits of total carbon for cast iron are taken as 2.0 and 4.5 per cent. The percentage of graphite is taken as from 1.0 to 4.0 for gray cast iron and from 0 to 1.0 for commercial white cast iron, and the remainder of the carbon is assumed to be present as Fe_3C. Few steels contain more than 1.5 per cent carbon, and few cast irons less than 3 per cent carbon; but the remaining classes (steel of from 1.5 to 2.0 per cent carbon) are here included so as to embrace the whole field of the iron-carbon compounds.

‡ While springs, cutting tools, and like objects may for convenience be regarded as belonging to this series, it is to be understood that in hardening them, and more particularly in tempering them, the austenito becomes much decomposed, passing towards the condition of ferrite and cementite. We have as yet little direct information as to the degree of this decomposition.

154. Summary. — To recapitulate, the chief constituents of the iron-carbon compounds, the steels and cast irons, are:

(1) in the slowly cooled state of both steel and cast iron, *pearlite,* a conglomerate of (2) the soft, weak, ductile *ferrite,* and (3) the hard brittle *cementite,* in the ratio of 6:1, together with whatever excess of ferrite or cementite is present over and above this ratio, (4) also in the slowly cooled state of cast iron, *graphite,* a non-metallic and as it were foreign body, (5) in the suddenly cooled state of both steel and cast iron, *austenite.*

We may classify all our iron-carbon compounds, all our steels and cast irons, according to this grouping.

155. Division of Iron into Three Series According to Microscopic Constitution. — In the slowly cooled state the metal will be either (1) pearlite with ferrite or cementite as the excess-substance, in which case we can call the whole series from carbon zero to carbon 4.50 per cent *the pearlite series;* or (2) pearlite plus ferrite or cementite as the excess-substance as before, but in addition graphite, in which case we can call the whole series the *graphito-pearlite series.* In general, but little graphite is present unless there is at least 2 per cent of total carbon, *i. e.,* it is only in cast iron that any important quantity of graphite is usually found. The graphito-pearlite series may then be called also the gray-cast-iron series.

In like manner we may call the suddenly cooled series, from carbon zero to carbon say 4.50 per cent, the *austenite series.*

In each series the metal is called " steel " if it contains less than two per cent of carbon, and " cast iron " if it contains more.

The theoretical constitution, the trade names, and the chief uses of the members of these three series are recapitulated in Table 7. These series are to be regarded as types to which any given piece of iron approaches more or less closely. Thus, while slowly cooled low-carbon and medium-carbon steel is usually exactly of the pearlite-series type, except in so far as its constitution is disturbed by the presence of manganese and other elements, yet slowly cooled high-carbon steel may vary slightly from the type by containing a small quantity of graphite. In particular it is doubtful whether any piece of metal is ever exactly of the austenite type, because no matter how sudden the cooling some of the austenite changes into or at least towards the ferrite and cementite condition, and because some of the carbon may, even after sudden cool-