plates of ferrite or iron, and cementite or the definite iron-carbide, Fe_3C, in the ratio of about 6 parts of the former to one of the latter.

187. GENESIS OF THIS CONSTITUTION. — While this has indeed already been treated at some length, especially in §§ 145 to 149, 169 and 172, yet a second presentation of the matter in a different and more concise form may be acceptable to some readers. To this end let us follow the cooling of steels of three typical compositions, viz., 0.90, 0.50 and 1.00 per cent of carbon respectively, i. e., eutectoid, hypo-eutectoid and hyper-eutectoid steel, looking particularly at the manner in which the constitution found in the steel when cold comes into existence, or in short, the genesis of this constitution. In each case let us suppose that the cooling metal has previously been cooled from the molten state to 1150°, at which temperature we have already seen (§ 168, p. 198), that the metal is unsaturated austenite.

188. (1) EUTECTOID STEEL, 0.90 per cent carbon. Austenite of this composition, or eutectoid austenite, has received the special name of "hardenite." In cooling this undergoes no transformation until the temperature has fallen to S. On passing S the hardenite is transformed into the eutectoid pearlite already described.

The cooling curve is like that of any eutectic, Figs. 10 and 28 E, and the correspondence is as follows:

Fig. 28E Fig. 68

AC	hS	The solid but red-hot hardenite cools.
CD	S	The hardenite is resolved into the eutectoid pearlite.
DE	Sh'	Pearlite cools.

189. (2) HYPO-EUTECTOID STEEL, 0.50 carbon. — In cooling from 1130°, h'', the first transformation begins on reaching the line HS at h'''. As the temperature begins to descend from this point to the point h^{IV} on the line PS, the excess-metal, iron or ferrite, begins to separate out within the plastic mass in the form of distinct grains or imperfect crystals, and this separation of ferrite within the plastic mass continues from h''' to h^{IV}.

This separation is clearly parallel with the selective freezing of lead from a lead-tin alloy rich in lead, or of ice from a salt-water solution. It is a progressive separating out of the excess-substance, iron, and is therefore accompanied by a correspond-

ing enrichment in carbon of the residual plastic mother-metal, so that as the temperature falls the composition and temperature of the mother-metal at successive instants are represented by points in the line HS between h''' and S, or in other words, the temperature and composition of the plastic mother-metal slide from h''' to S. Consequently by the time the temperature has fallen to 690° or h^{IV}, the mother-metal has reached the eutectoid composition of hardenite, and simultaneously the eutectoid transformation temperature. On farther fall of temperature this hardenite splits up into alternate layers of ferrite and cementite, or in other words is resolved into pearlite.

The cooling curve is like that of an alloy of two metals reciprocally insoluble, such as lead and tin, Fig. 28 B, C, D and F, or like that of salt water, Figs. 8, 9 and 11.

The correspondence is as follows:

Figs. 28 B, C, D, etc.   Fig. 68

AB	$h''h'''$	Hypo-eutectoid red-hot austenite cools.
BC	$h'''h^{IV}$	The excess-substance, ferrite, separates out, and the mother-metal is enriched in carbon till it becomes hardenite, i. e., austenite of 0.9 per cent carbon.
CD	h^{IV}	Hardenite is resolved into pearlite.
DE	$h^{IV}h^{V}$	The conglomerate of pearlite plus ferrite cools.

190. (3) HYPER-EUTECTOID STEEL, 1 per cent carbon, $r'W$. The cooling is undisturbed from r' 1130° until the temperature falls to L on line SE, but here the excess-substance, carbon, begins to form or separate out in the shape of crystallites of cementite permanently imprisoned within the plastic metal in which they are born. The cementite continues to form as the temperature falls from L to U on the line PSP'. This birth of cementite like the birth of ferrite in the last case, is parallel with the freezing out of the excess-metal from a molten alloy of the complete insolubility type, or of salt from salt water. The separating out from the initial austenite of the crystallites of cementite, which contain 6.67 per cent carbon, impoverishes the mother-metal in the excess-substance, carbon, and enriches it in the deficit-substance, iron, and this impoverishment in carbon continues as the temperature falls, so that, as it were, temperature and composition slide

along the line *LS*. Hence when the temperature has fallen to the eutectoid transformation-point, *S*, the composition of the mother-metal has reached this same point, or in other words, the austenite has been impoverished in carbon until it has reached the hardenite ratio 0.90 per cent carbon, 99.10 per cent iron.

With further cooling this hardenite as before splits up into pearlite, at approximately constant temperature, *S*, and once this transformation is complete the further cooling is without any further transformation that requires our present attention.

The cooling curve is like that of the hypo-eutectoid steel and therefore like that of any alloy of two metals of the complete insolubility type, Figs. 28 *B* to 28 *D*, *etc*. The correspondence is as follows:

Figs. 28*B* to 28*D*, *etc*.	Fig. 68	
AB	*r'L*	Red-hot plastic hyper-eutectoid steel cools.
BC	*LU*	Cementite, the excess-substance, forms within the plastic mass impoverishing the mother-metal in carbon till it reaches the hardenite ratio, 0.90 carbon.
CD	*U*	The hardenite mother-metal splits up into pearlite at approximately constant temperature.
DE	*UW*	The conglomerate of pearlite plus cementite further cools.

Transformations parallel with those in solid iron appear to occur in some alloys when solid, for instance those of copper and tin,* and those of copper with antimony, Fig. 51, p. 150.

191. DIFFERENT ALLOTROPIC STATES. — A complication is introduced by the fact that the iron of the austenite of region IV is in an allotropic condition different from that of the iron which is liberated as ferrite as the metal cools from region IV into regions V and VI. In region IV the iron in the austenite is in the allotropic state known as *gamma* (γ) iron; but the iron liberated as ferrite by the transformation in passing from region IV into that part of region V which lies above the line *MH*, is in the *beta* (β) state. Moreover when the temperature falls past the line *MH* this *beta* iron again changes to *alpha* (α) iron.

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* Wm. Campbell, " Microscopical Examination of the Alloys of Copper and Tin," *Proc. Inst. Mechanical Engineers*, Dec. 20, 1901.

192. SPECIAL NOMENCLATURE OF THE TRANSFORMATION CURVES, *GHSE, PSP'*. — In order to indicate with precision the nature of the changes which correspond to each of the steel transformation curves, and further to indicate clearly the correspondence between the transformations during cooling and those during rise of temperature, Osmond instituted a special set of names, now in general use, based upon Tschernoff's original nomenclature.

The temperature at which *gamma* iron changes to *beta* (which is the temperature at which free iron or ferrite begins to separate out of the austenite, *e. g.*, *K'* in the case of the 0.20 per cent carbon steel), is known as Ar_3; that at which *beta* changes to *alpha* is known as Ar_2; that finally at which the residual mother-austenite which has remained undecomposed during the fall from *K'* to *K'''* and at *K'''* changes into pearlite, is known as Ar_1.

Between *H* and *S*, Ar_3 and Ar_2 occur together, as do Ar_2 and Ar_1 between *S* and *P'*, and Ar_3, Ar_2, and Ar_1 at *S* itself; so that these critical points in these special cases are called Ar_{3-2}, Ar_{2-1}, and Ar_{3-2-1} respectively. The corresponding critical points which occur during rise of temperature, with the reverse transformations, are called Ac_1, Ac_2, Ac_3, *etc*. Here A (Tschernoff) is their generic name, r refers to falling temperature (refroidissant), and c to rising temperature (chauffant).

When A_1 is spoken of without indicating whether Ar_1 or Ac_1 is referred to, it should be understood that this transformation is looked at in a general way, both the Ac_1 transformation in heating and the Ar_1 transformation in cooling being in mind.

As to the shifting of the temperature of these transformation curves see the last part of § 164, p. 196.

193. PROPERTIES OF THE ALLOTROPIC STATES. — As to the properties of these three allotropic states of iron a word may not be out of place.

Alpha iron is iron in the state in which we habitually know it in the softest and most ductile varieties of steel and wrought iron, a relatively weak, ductile metal strongly magnetic. This is the variety stable at all temperatures below Ar_2 and is characteristic of wrought iron and slowly cooled low-carbon steel. In other words, the molecules of iron which constitute the ferrite of wrought iron and low-carbon steel are apparently in the *alpha* state, a fact which harmonizes with the softness and ductility of these varieties of iron. Doubtless this softness is to be referred

in chief part to the fact that these varieties are composed chiefly of the soft ferrite and in only small part of the glass-hard cementite; but the ductility and softness are probably exaggerated by the fact that this ferrite is in the *alpha* state, instead of being in the *beta* or *gamma* state. There is important evidence in support of this view.

Beta iron is non-magnetic (in the usual sense of being very feebly magnetic), is stable between Ar_2 and Ar_3, is probably very hard and brittle, and is probably characteristic of certain self-hardening steels, such as manganese steel containing 7 per cent of manganese, and perhaps also of normal or carbon steel when hardened by sudden cooling from a red heat.

Gamma iron also is non-magnetic, and it is stable at temperatures above Ar_3. It is probably characteristic of nickel and high-manganese steels (say of 12 to 14 per cent of manganese), and is probably relatively hard yet ductile.

That iron becomes stronger, harder, and less ductile as its carbon-content increases, must be in very great part referred to the mechanical influence of the cementite, Fe_3C, which that carbon forms, in the ratio of 15 parts of cementite to each part of carbon; but it also may be due to the brake action of this carbon, inducing part of the free iron or ferrite to remain, during its cooling from the high temperature at which it is cast or forged, in one of its harder and stronger allotropic states, *beta* or *gamma*.

194. Transformation Parallel with Freezing. — To recapitulate, our transformation phenomena in steel in its critical range are closely parallel with those that occur in the freezing of a lead-tin alloy, or a salt-water solution. Thus, our slowly cooled steel will consist of pearlite plus an excess of cementite or of ferrite according to whether carbon is present in excess above the pearlite ratio 0.90 per cent, or is below that ratio. The V-shaped transformation curves, the horizontal transformation line PSP' which underscores them, the separation of an excess-substance beginning at the V-shaped curves, the corresponding progressive change of the mother-metal in composition until at the transformation line PSP' it reaches the hardenite ratio, the ensuing transformation of the hardenite into interstratified plates of its components in the form of pearlite, the fact that the pearlite is of constant composition, independent of the initial composition, and that its composition is not in simple atomic ratio; the occurrence

of surfusion giving rise to the recalescence; all these facts are exactly parallel with what occurs in the freezing of a eutectiferous alloy. Pearlite, the eutectoid, differs from a true eutectic only in being generated by a transformation within a plastic solid, instead of by the solidification of a fluid. Hardenite is the untransformed, pearlite the transformed and split eutectoid.

CHAPTER IX. — THE HEAT-TREATMENT OF STEEL AND CAST IRON

195. The Heat-treatment of Steel and Cast Iron. In General. — The properties of steel and cast iron can be modified profoundly by thermal treatment. The two chief principles involved are the control of the lagging reactions, especially (4), (9) and (10), and the control of the structure.

By the control of the lagging reactions, I mean causing them to occur to a predetermined degree, so as to control the proximate constitution of the alloy, for instance so as to give it exactly the desired proportion of austenite on one hand, and of ferrite and cementite on the other. We control these reactions either by restricting them by proper rapidity of cooling when they naturally tend to occur spontaneously in the cooling of the metal from the high temperature at which it is made, cast, forged, or rolled; or by stimulating them so as to cause them to occur to a greater degree than would be natural under normal conditions of cooling. The reactions upon which we play are probably chiefly the following:

(4) molten solution $=$ 2 per cent austenite $+$ graphite (§§ 166 and 167, pp. 197 and 198);

(9) austenite $=$ ferrite $+$ cementite (§ 169, p. 199), and

(10) graphite $+$ austenite $=$ cementite (§ 172, p. 200).

Reaction (9) is characteristic of both steel and cast iron; reactions (4) and (10) are characteristic of cast iron only.

While all three of these reactions are subject to lag, *i. e.*, while they all take an appreciable length of time, reaction (9) is very much more rapid than either of the others. It appears to take usually at most but a few minutes, whereas reactions (4) and (10) are much slower. Reaction (4) indeed, for reasons already