

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

pointed out, occupies several days, as in the annealing operation in the manufacture of malleable cast iron. (§ 227, p. 281.)

By control of the structure we determine the size and arrangement of the individual grains or crystallites of the several microscopic constituents.

Most methods of heat-treatment actually control both the proximate constitution and the structure.

Let it not be supposed that, because the principles of heat-treatment can thus be formulated with precision, the exact proportions of the constituents and the exact structure developed by certain procedure are known with corresponding accuracy. So far is this from being true, that our knowledge even of the outward effects of heat-treatment upon the useful properties such as tensile strength is extremely fragmentary; while as to even the explanation of the processes of heat-treatment our knowledge is most incomplete. The following explanations are given as at least consistent and reasonable. If a positive form of statement is often used, it is to avoid the endless and bewildering repetition of cautions as to the lack of conclusive proof of the theories set forth.

We will now go on to consider certain processes, the hardening of steel, the chilling of cast iron, etc., which act chiefly through controlling these lagging reactions. And first let us note the influence of lag upon the shape of the cooling curves.

Processes Operating Chiefly through Control of the Proximate Constitution

196. DEFORMATIONS OF THE COOLING CURVES BY LAG. — If, as we saw in § 30, changes of state from liquid to solid or to gas, accompanied as they are by such tremendous changes of energy, can through one cause or another be prevented from occurring at their normal temperature, so that a liquid may remain liquid for many degrees outside the temperature limits which normally bound the liquid state, very far above the boiling-point at one end, and far below the freezing-point at the other, — it is no wonder that the relatively mild transformations in solid iron and in other metals should, through means akin to surfusion, be so obstructed that they do not occur promptly when

their normal temperatures are reached. In fact these changes may not actually set in until the temperature has passed much beyond the normal boundary temperature, and may then occur slowly; and thanks to this slowness they may even be arrested, by cooling the metal rapidly to a temperature so low that the feeble force tending to the transformation is unable to overcome what we may call the molecular rigidity which the cold induces.

These transformations in general are thus spread out so much as to deform the cooling curves very greatly, and indeed they can be made much clearer by plotting the data after a different plan, *viz.*, by using as abscissæ not time reckoned from the beginning of the record, but the interval of time occupied in passing from each degree (or fraction of a degree) to the next. Fig. 12 is plotted on this plan, as also is Fig. 69, p. 220, the cooling curve of hyper-eutectoid steel. The latter is lettered conformably with the cooling curve in Fig. 31.

From *A* to *B* the austenite cools undisturbed; at *B* cementite, the excess-substance, begins forming, *i. e.*, crystallizing out within the plastic mass, and thus impoverishing the mother-metal in carbon. This continues from *B* to *C*, at which point the mother-metal, now become hardenite, is transformed into the eutectoid pearlite.

197. THE RECALESCENCE.* — In particular, the transformation of the eutectoid austenite into pearlite (reaction (9), at *Ar*, *PSP*, Fig. 68) does not begin habitually until the temperature has sunk considerably below the normal transformation temperature, while the reverse transformation on heating steel does not take place till the temperature has risen appreciably above this point.

When, however, reaction (9) does set in, it takes place so rapidly and with such evolution of heat, that the temperature rises abruptly, quite as in the case of surfusion shown in Figs. 14 and 15, pp. 35-7, so that the metal brightens visibly and reexpands. This phenomenon is known as the recalescence. It is probable, however, that the rise of temperature does not reach the true transformation temperature: at least it does not pass it, so that the transformation of hardenite into pearlite is not arrested. The sharp peak at *CD*, Fig. 69, represents this recalescence.

* For a method of detecting the recalescence, see § 208, p. 235.

In this figure ordinates represent temperature, while abscissæ represent, not time from the beginning of the observation, but the interval of time occupied in cooling through a given number of degrees Centigrade. Point *B* represents the upper limit of region VIII, *i. e.*, A_{r_3} . The part *DE* is not given in the original, but is sketched in here by eye.

This phenomenon is by no means an isolated one. Person reported in 1847 a like recalescence by d'Arcet's alloy, which solidi-

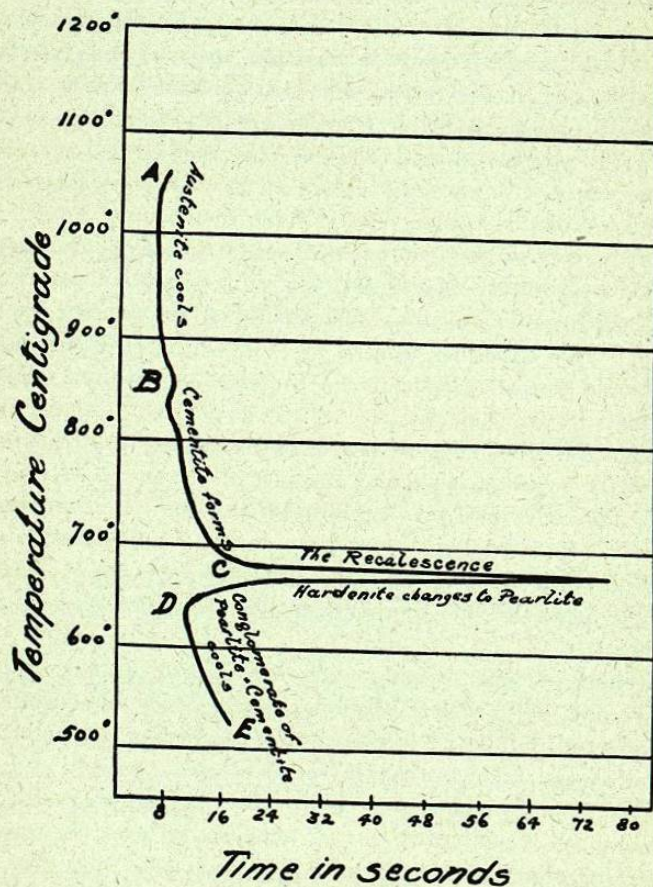


Fig. 69. Retardations in the Undisturbed Cooling of Hard Steel of 1.25 per cent Carbon.

(F. Osmond, "Transformations du Fer et du Carbone dans les Fers, les Aciers et les Fontes Blanches," Paris, 1888, pl. 2.)

fies at 96° , then cools regularly to 57° and then suddenly recalesces one or two degrees.*

This actual rise of temperature through the rapid evolution of heat due to the rapidity of the transformation once it sets in well, reminds us of the bumping of solutions. They rise very slightly above their proper boiling-point, boiling begins, and because this temperature is above the true boiling-point the boiling is violent, or bumping.

198. THE HARDENING AND TEMPERING OF STEEL.—The foregoing puts us in a position to understand the more prominent features of the heat-treatment of steel, such as hardening, tempering, *i. e.*, mitigating the hardening, and annealing.

To recapitulate, if steel is cooled suddenly from above the critical range A_1 to A_3 , it is thereby made harder and less ductile or even extremely brittle, and is said to be "hardened." The degree to which it is thus hardened increases with the carbon-content, so that, whereas very low-carbon steel is affected only very slightly, steel with 1.00 per cent of carbon is made as hard and nearly as brittle as glass.

The hardness and brittleness induced increase with the rapidity of cooling without limit, but they are apparently nearly independent of the temperature from which the sudden cooling begins, provided that this is distinctly in regions IV or VII of Fig. 68, *i. e.*, provided that the quenching temperature is above the transformation range, regions V and VIII of Fig. 68. As, in a series of pieces quenched from different temperatures, the quenching temperature progressively rises from specimen to specimen through the transformation range, so do the resultant hardness and the brittleness of the quenched steel. In short, the hardening power is acquired in rising through the transformation range, and is lost progressively in slow cooling through that range.

The tensile strength at first increases with the intensity of hardening, but reaches a maximum and then declines. In case of high-carbon steel a moderate rapidity of cooling may give the highest tensile strength; but in case of low-carbon steel the tensile strength seems to increase with rapidity of cooling without limit.

* *Comptes Rendus*, XXV, p. 444, 1847.

Hardened steel is "tempered," *i. e.*, the hardening is mitigated or let down, by slight reheating, say to 200° or 300°; and the steel is "annealed," *i. e.*, the hardening is completely removed, by reheating farther, say to 600°. After this reheating to 200° or 300° it is immaterial whether the steel is then cooled suddenly or slowly; the degree of tempering is the same in either case; and the same is substantially true of the higher heating to 600°, or *annealing*.

The reason why this sudden cooling from above the critical range thus hardens and embrittles steel is, as is now generally admitted, that the rapid cooling denies the time needed for the completion of the change from the condition of austenite into that of ferrite and cementite, with the consequence that the suddenly cooled steel actually consists of austenite, which is much harder and more brittle than the mixture of ferrite and cementite into which the steel tends to change at all temperatures below the critical range.

The tendency to change appears to increase as the temperature passes farther and farther from the normal transformation temperature; but as the temperature descends, a resistance to this change arises, a resistance which grows more rapidly than the tendency to change; so that by the time the metal has reached the room-temperature, the change, which is still tending to occur, is prevented by this resistance which we may assume provisionally is frictional in its nature. In hardened steel the molecules are locked in the abnormal condition of austenite by what we may call the frictional resistance of the cold. This will be farther elucidated in § 201, p. 225.

The pearlite, either alone or with the excess of ferrite or cementite, into which austenite is resolved in slow cooling, is much softer and more ductile than austenite, in spite of the fact that cementite itself is harder than austenite. But this cementite is accompanied by a quantity of ferrite so great as to outweigh greatly its influence. Thus, slowly cooled steel containing 1.00 per cent of carbon would have only 15 per cent of cementite, mixed with 85 per cent of ferrite. The bearing of this is of course uninfluenced by the fact that the 85 per cent of ferrite together with 13 out of the 15 per cent of cementite, are interstratified as pearlite, so that the steel consists of $85 + 13 = 98$ per cent of pearlite plus 2 per cent of free cementite, *i. e.*, cementite in excess

of the eutectic ratio, and hence structurally free from that pearlite.*

The higher the carbon-content of the steel as a whole, (1) the higher is the carbon-content of the austenite which is preserved by sudden cooling, and (2) the harder is the suddenly cooled steel. Fact (2) may be referred to fact (1), or to the apparent brake action of the carbon which retards the transformation from the hard, *beta* or *gamma* brittle iron to the soft, ductile *alpha* iron; or better to both causes jointly.

The much greater hardness of austenite than of the mixture of ferrite and cementite into which it is resolved in slow cooling, suffices to explain readily the hardness and brittleness which its retention by sudden cooling causes, and there is general agreement that this is the cause of the hardening, though as to the constitution of austenite it appears that some have not yet been convinced.

199. THE HARDENING INCREASES AS THE QUENCHING TEMPERATURE RISES THROUGH THE CRITICAL RANGE, BUT IT IS INDEPENDENT OF THE TEMPERATURE ABOVE THAT RANGE.—The following table shows how the tensile strength and hardness of

* Should it appear strange that hardened steel is actually very much harder, indeed incomparably harder, than the same steel when annealed, in spite of the fact that the cementite present in the latter is actually harder than the austenite of which the former consists, a simile may explain the apparent anomaly.

To fix our ideas let us consider the case of eutectoid steel, which when annealed consists of about 6 parts by weight of ferrite to each part of cementite. Compare with the steel in its hardened and its annealed states respectively (1) bronze, and (2) a mechanical mixture of finely-ground dust of glass in impalpable powder with six times its volume of lead. (Those unfamiliar with the properties of bronze and lead may substitute putty for lead in this comparison.)

Such a mixture of glass dust with an overwhelming excess of lead, while doubtless stiffer and harder than the lead alone, must clearly be incomparably softer than a like mass of solid bronze, although the glass itself is much harder than that bronze. Quite so the mixture of which our annealed steel consists, of one part of hard cementite in impalpably fine grains with an overwhelming excess of soft copper-like ferrite, is naturally softer as a whole than a mass of austenite of which hardened steel consists, although the cementite in the annealed steel is itself harder than that austenite. The thing to look at is the great excess of the soft ferrite in which the microscopic particles of cementite in annealed steel are drowned.

TABLE 9. — Influence of Quenching Temperature on the Physical Properties, Carbon Condition, and Micro-structure of Steel of 0.21 per cent of Carbon. (Howe and Sauveur.*)

No.	Quenching Temperature Degrees C.	Tenacity, Pounds per Square Inch	Hardness, Width of Scratch, mm.	Elongation		Contraction of Area, per Cent	Missing Carbon, per Cent	Micro-structural Composition, per Cent		
				Per Cent	Inches			Martensite	Pearlite	Free Ferrite
6	880	224,600	—	3.50	2.5	—	0.092	100	—	0
7	836	207,500	0.0276	3.00	4	5	0.095	100	—	—
4	797	218,200	0.0285	6.00	4	—	0.102	100	—	—
16	761	193,516	—	1.25	4	1.01	0.082	100	—	—
15	733	220,898	0.0290	4.50	4	—	0.095	100	—	—
12	714	221,300	0.0281	7.50	4	—	0.102	97.20	—	2.80
18	713	211,316	0.0303	2.50	4	1.54	0.093	86.00	—	14.00
9	698	206,673	0.0293	3.75	4	3.53	0.096	70.20	—	29.80
5	652	145,000	—	2.25	4	3.17	0.100	35.20	—	64.80
14	650	142,000	0.0298	4.75	4	5.68	0.084	30.80	—	69.20
21	633	128,237	0.0333	4.25	4	5.87	0.084	32.00	—	68.00
10	626	125,756	0.0320	5.50	4	5.94	0.084	31.50	—	68.50
22	620	121,058	0.0329	6.25	4	5.60	0.091	30.00	1.60	68.40
11	600	91,600	0.0333	13.50	4	44.40	0.034	4.00	17.50	78.50
3	599	89,000	0.0332	13.00	4	46.50	0.047	2.00	22.20	75.80
8	575	93,400	0.0343	19.75	4	38.60	0.029	—	21.10	78.90
19	532	82,771	0.0343	21.25	4	51.34	0.005	—	23.20	76.80
13	512	82,100	0.0356	26.00	4	54.40	0.018	—	23.00	77.00
17	340	79,362	—	23.75	4	53.34	0.000	—	22.60	77.40
20	263	76,523	—	22.50	4	55.04	0.000	—	24.80	75.20
23	20	73,956	0.0365	25.75	4	52.29	0.008	—	23.60	76.40
24	Not treated	93,707	0.0331	18.75	4	53.89	—	—	—	—
25	at all	94,340	0.0331	17.50	4	51.14	—	—	—	—
Total loss or gain		150,644	0.0089	22.75	—	—	0.102	—	—	—

* Journ. Iron and Steel Inst., 1896, I, p. 171, Table I.

steel of 0.21 per cent carbon increase as the quenching temperature rises through the critical range (600° to 714°), how the ductility correspondingly diminishes, and how the pearlite and ferrite are progressively replaced by austenite (variety martensite). The table further shows when once the quenching temperature has risen above the transformation range (733°), further rise of the quenching temperature is without material influence on the properties of the hardened steel.

200. THE HARDENING INCREASES WITH THE RAPIDITY OF COOLING WITHOUT LIMIT. — The following table illustrates this fact:

TABLE 10. — Influence of the Rapidity of Quenching on the Properties of Steel of 0.21 per cent of Carbon. (The Author.*)

(The steel experimented on is the same which is represented in Table 9)

COOLED IN	TENSILE STRENGTH lbs. per sq. in.	ELASTIC LIMIT lbs. per sq. in.	ELONGATION per cent in 2 inches	CONTRACTION OF AREA per cent
Iced Brine	237,555	237,170	2.0	1.30
Cold water	216,215	—	1.5	1.67
Oil	174,180	—	2.9	1.403
Air	86,797	54,342	27.76	57.829
In furnace	80,103	44,221	28.15	54.749

Here the tensile strength was increased about three-fold while the ductility, originally very great, was nearly completely destroyed by the most rapid of the coolings employed.

Further, as the rapidity of cooling increases from case to case, so does the tensile strength increase continuously and the ductility decrease but more suddenly.

201. LIKE PHENOMENA IN ALLOTROPIC CHANGES. — We saw in §§ 194 and 197, pp. 216 and 219, that the phenomena of the recalescence of steel, the surfusion and reheating, are closely like those of both aqueous solutions and molten metals and alloys in freezing. It is instructive to note both sets of phenomena are like those of the allotropic changes of state in solids. Thus in case of sulphur the prismatic state is the normal and stable one at temperatures between 95.6° and its melting-point, but the octahedral

* Unpublished data.