CHAPTER IV.

THE THERMAL TREATMENT OF METALS.

Annealing, Hardening, and Tempering.—The mechanical properties of metals are often, in a great measure, dependent on the thermal treatment to which they have been subjected. There can be no question that the application of heat to a metal may produce a remarkable molecular change in its structure, the nature of the change depending on that of the metal or alloy, and on the treatment it has undergone. It will be well, therefore, to consider carefully what happens when metals are submitted to the three principal operations involving thermal treatment, which are known respectively as **annealing**, **hardening**, and **tempering**. Usually all three are intimately related. Annealing may be defined as the release of strain in metals, which may itself have been produced by mechanical treatment, such as hammering, rolling, or wiredrawing, or by either rapid or slow cooling from a more or less elevated temperature. As an example of the former, it may be mentioned that metals and alloys which have been rendered excessively hard by rolling are heated usually to bright redness and allowed to cool slowly. In the case of copper, it does not appear to be important whether the cooling is slow or rapid, and in recent years much experimental evidence has been accumulated which tends to show that in the case of certain metals which have been hardened, a more or less prolonged exposure to a temperature under 100° will sensibly anneal them. With some metals and alloys, the rapidity with which the cooling is effected is very important. Bronze containing about 20 per cent. of tin[1] is rendered very malleable by rapid cooling. It is, however, in the case of iron and steel that thermal treatment is especially important, although many other alloys may undergo important changes in properties by varying the thermal treatment.

Steel, it must be remembered, is modified iron. The name "iron" is, in fact, a comprehensive one, for the mechanical behaviour of the metal is so singularly changed by influences acting from within and without its mass as to lead many to think, with Paracelsus, that iron and steel must be two distinct metals, their properties being so different. Pure iron may be prepared in a form pliable and soft as copper, steel can readily be made sufficiently hard to scratch glass; and notwithstanding this extraordinary variance in the physical properties of iron and certain kinds of steel, the chemical difference between them is comparatively very small, and would hardly secure attention if it were not for the importance of the results to which it gives rise. It is necessary to consider the nature of the transformations which iron can sustain, and to see how it differs from steel, of which an old writer has said:[2] "Its most useful and advantageous property is that of becoming extremely hard when ignited and plunged in cold water, the hardness produced being greater in proportion as the steel is hotter and the water colder. The colours which appear on the surface of steel slowly heated direct the artist in *tempering* or reducing the hardness of steel to any determinate standard." There is still so much confusion between the words "temper," "tempering," and "hardening," in the writings of even very eminent authorities, that it is well to keep these old definitions carefully in mind. **Hardening** is the result of rapidly cooling a strongly heated mass of steel. **Tempering** consists in modifying or reducing the hardness by heating the hardened steel to a temperature far short of that to which it was raised before hardening; this heating may or may not be followed by rapid cooling. **Annealing**, as applied to steel, consists in heating the mass to a temperature higher than that used for tempering, and allowing it to cool slowly.

The effects of the above treatments may be illustrated by taking a strip of steel and cutting it into three pieces. One piece can be bent cold, showing that it is soft; but if it is heated to redness and plunged in cold water it will become hard, and will break on any attempt to bend it. The second piece may, after heating and rapid cooling, be again heated to about the melting-point of lead, when it will bend readily, but will spring back to a straight line when the bending force is removed. The third piece may be softened by being cooled slowly from a bright red heat, and this will bend easily and will remain distorted.

The metal has been singularly altered in its properties by comparatively simple treatment, and all these changes, it must be remembered, have been produced in a solid metal to which nothing has been added, and from which nothing material has been taken away.

The theory of the operation described above has been laboriously built up, and its consideration introduces many questions of great interest, both in the history of science and in our knowledge of molecular physics.

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[1] Riche, *Ann. de Chim. et de Phys.*, vol. xxx. (1873), p. 417.

[2] *The First Principles of Chemistry*, by W. Nicholson, London, 1760, p. 312.

History.—First, as regards the history of the subject. The knowledge that steel might be hardened must have been derived from remote antiquity. Copper hardened with tin was its only predecessor, and it continued to be used very long after it was known that steel might be hardened. It would, moreover, appear that a desire to appreciate the difficulties of a people to whom cutting instruments of hard steel were unknown, seems to have induced experimenters in quite recent times to fashion implements of bronze, and a trustworthy authority states that "Sir Francis Chantry formed an alloy containing about 16 parts of copper, $2\frac{1}{2}$ of zinc, and $2\frac{1}{2}$ of tin, of which he had a razor made, and even shaved with it."[1] The Greek alchemical MSS., which have been so carefully examined by M. Berthelot, give various receipts, from which it is evident that in the early days the nature of the quenching fluid was considered to be all-important. There were certain rivers the waters of which were supposed to be specially efficacious. Pliny, who says that the difference between waters of various rivers can be recognised by workers in steel, also knew that oil might be used with advantage for hardening certain varieties of the metal. It is sad to think how many of the old recipes for hardening and tempering have been lost. Theophilus, writing in the eleventh century, gives very quaint instructions in the art of hardening steel. The belief, however, in the efficacy of curious nostrums and solutions for hardening steel could hardly have been firmer in the third century B.C. than in the sixteenth of our era. Pure cold water is now usually employed for hardening, but it was far too simple a material for many a sixteenth-century artificer to employ, as is shown by the quaint recipes contained in one of the earliest books of trade secrets, which, by its title, showed the existence of the belief that the "right use of alchemy" was to bring chemical knowledge to bear upon industry. The earliest edition was published in 1531,[2] and the first English translation[3] in 1583, from which the following extracts may be of interest. "Take snayles, and first drawn water of a red die, of which water being taken in the two first monthes of harvest when it raynes," boil it with the snails, "then heate your iron red hot and quench it therein, and it shall be hard as steele." "Ye may do the like with the blood of a man of xxx years of age and of a sanguine complexion, being of a merry nature and pleasant . . . . distilled in the middst of May." This may seem trivial enough, but the belief in the efficacy of such solutions survived into the nineteenth century, for in a work published in 1810 the artist is

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[1] *Engines of War*, by H. Wilkinson, 1841, p. 194.

[2] *Rechter Gebrauch d. Alchimei*, 1531. There were many English editions.

[3] "A profitable boke declaring dyuers approoued remedies," etc., London, 1853. See Prof. Ferguson's learned paper "On some Early Treatises on Technological Chemistry," *Phil. Soc. Glasgow*, Jan. 1886, vol. xvii. p. 206.

prettily directed[1] "to take the root of blue lilies, infuse it in wine and quench the steel in it," and the steel will be hard; on the other hand, he is told that if he "takes the juice or water of common beans and quenches iron or steel in it, it will be soft as lead." As must always be the case when the practice of an art is purely empirical, such procedure was often fantastic, but it is by no means obsolete, for probably at the present day there are many workshops in which some artificer could be found with a claim to possess a quaint nostrum for hardening steel. Even the use of absurdly compounded baths was supported by theoretical views. Otto Tachen,[2] for instance, writing of steel in about the year 1666, says that steel when it is "quenched in water acquires strength, because the light alcaly in the water is a true comforter of the light acid in the iron, and cutlers do strengthen it with the alcaly of animals," hence the use of snails. Again, Lemery[3] explains in much the same way the production of steel by heating iron in the presence of horns of animals.

These points have been dwelt upon in order to bring out clearly the fact that the early workers attached great importance to the nature of the fluid in which hot steel was quenched, and they were right, though their theories may have been wrong. The degree of rapidity with which heat is abstracted from the steel during the operation of hardening is as important at the present day as it ever was. Roughly speaking, if steel has to be made glass-hard, ice-cold water, brine, or mercury is used; if it has only to be made slightly hard, hot water or oil may be employed; while, as Thomas Gill[4] suggested in 1818, both "hardening" and "tempering" may be united in a single operation by plunging the hot metal in a bath of molten lead or other suitable metal, which will, of course, abstract the heat more slowly.

The use of lead and of other metals in hardening steel has, however, long been known. Réaumur[5] described in 1722 a method of hardening the points of tools by forcing them when hot into *solid* tin and lead, and he hints at the use of solid masses of gold, silver, and copper as cooling metals. This old work blends curiously into the new, for the cold metallic surfaces suggested by Clémendot[6] doubtless play an important part in his process of hardening by compression; whilst another process, that of hardening by water spray, which is used in connection with the manufacture of armour-plate, is at least a century old.[7]

Probably the earliest reference to the use of mercury as a

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[1] *The Laboratory; or School of Arts*, 6th edition, 1739, p. 126. There is a later edition of 1810.

[2] *Key to the Ancient Hippocratical Learning*, London, 1690, p. 68.

[3] *A Course of Chymistry*, 2nd edition, 1686, p. 131.

[4] Thomson's *Annals of Philosophy*, vol. xii. (1818), p. 58.

[5] *L'art de convertir le fer forgé en acier*, Paris, 1722, p. 351.

[6] *Comptes Rendus*, vol. xciv. (1882), p. 703.

[7] Guyton de Morveau, *Encyc. Méthodique*, Paris, 1786, p. 436.

cooling fluid is that made by Rèaumur; but in no direction has the modern development of hardening processes been more important than in connection with the use of baths, in which the fluid, being a molten metal, is not readily vaporised. Lisbonne[1] has shown what remarkable results as regards resistance to penetration have attended the adoption of the process of hardening armour-plates in lead baths, which, as Everard[2] shows, must be capacious and not heated above the melting-point of lead, his experiments leading to the conclusion that armour-plates so quenched in lead are very difficult to penetrate, and present great resistance to fracture.

Internal Constitution of Steel.—The development of theories relating to the internal constitution of steel must now be traced. The advent of the Phlogistic school with the teaching of Becher and Stahl led to the view that iron gained phlogiston during its conversion into steel. By phlogiston the early chemists really meant *energy*, but to them phlogiston was represented to be a kind of soul possessed by all metals, which they could lose by burning and regain by the process they called "revivication." "Hardness [in metals] is caused by the jeiunenesse of the spirit and their imparity with the tangible parts," said Francis Bacon;[3] while, according to Stahl,[4] steel was merely iron possessing, in virtue of its phlogiston, the characteristics of a metal in a higher degree, and this view prevails in the writings of Henckel, Newmann, Cramer, Gellert, Rinman, and Macquer. This opinion survived with wonderful persistence, but it did not influence the teaching of Réaumur,[5] who, in 1722, was the first to suggest a physical theory which has been in any way justified by modern research. He assumed that when steel was heated, "sulphurs and salts" were driven out from the molecules, which he represents diagrammatically, into the interstitial space between them. The quenching of the steel and its sudden cooling prevented the sulphurs and salts from returning into the molecules, which were thus firmly cemented by the matter between them, and hard, rigid steel was the result. In tempering, the sulphurs and salts partially returned into the molecules, and the metal became proportionately soft. He used the Torricellian vacuum to demonstrate that the hardening of steel is not accompanied by the evolution of gas; and he concluded that "since the hardening of steel is neither due to the intervention of a new substance nor to the expulsion of air, it only remains to seek its cause in the changes occurring in its structure." Notwithstanding this, the

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[1] *Génie civil*, vol. xiii. (1888), p. 22.

[2] Paper read at the International Congress of Mining and Metallurgy, Paris, 1889.

[3] *Sylva Sylvarum*, 2nd edition, 1628, p. 215.

[4] *Fundamenta Chemiæ*, part iii. p. 451, quoted by Guyton de Morveau in the article "Acier," *Encyc. Méthodique*, p. 421, Paris, 1786.

[5] *L'art de convertir le fer forgé en acier*, Paris, 1722, p. 321 *et seq.*

Phlogistic school were not daunted; and this leads directly to the work of Torbern Bergman, the great Professor at the University of Upsala, who, in 1781, showed[1] that steel mainly differs from iron by containing about $\frac{2}{10}$ per cent. of plumbago, while iron does not. Read in connection with modern research, his work seems wonderfully advanced. He was so forcibly impressed by the fact that the great difference in the mechanical properties of different specimens of iron is due to the presence of small quantities of impurity, and that the properties of iron do not vary, as he says, unless by chance the iron has gathered foreign matter, "*nisi forte peregrinum paullo uberius inhæreat metallum*," in which sentence there is even the dawn of the view that, under the influence of small quantities of foreign matter, iron is, as he calls it, polymorphous, and plays the part of many metals. "*Adeo ut jure dici queat, polymorphum ferrum plurium simul metallorum vices sustinere.*"[2] Unfortunately he confounded the plumbago or carbon he had isolated with phlogiston, as did Rinman in 1782, which was strange, because in 1774 the latter physicist had shown that a drop of nitric acid simply whitens wrought iron, but leaves a black stain on steel. Bergman tenaciously held to the phlogistic theory in relation to steel; it was inevitable that he should. The true nature of oxidation had been explained; no wonder that the defenders of the phlogistic theory should seek to support their case by appealing to the subtle and obscure changes produced in iron by such apparently slight causes. Bergman's view was, however, combated by Vandermonde, Berthollet, and Monge,[3] who showed in a report communicated to the *Académie des Sciences* in 1786 that the differences between the main varieties of iron is determined by variation in the amount of carbon; and further, that steel must contain a certain quantity of carbon in order that it might possess definite qualities. Bergman died in 1784, and the report to which reference has been made is full of respect for "this grand chemist," as its authors call him, "whom science had lost too soon."

Kirwan's essay on Phlogiston,[4] in which Bergman's views were defended, elicited a reply from Lavoisier himself, and brought down the French school in strength to contest almost the last position occupied by the believers in phlogiston.[5]

Bergman's was almost the first calorimetric work, and it is impossible to read it without feeling that in paying the just tribute to Lavoisier's genius, Bergman has been overlooked. He desired

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[1] *Opuscula Physica et Chemica*, vol iii., Upsala, 1783; *De Analysi Ferri*, a dissertation delivered June 9, 1781.

[2] *De Analysi Ferri*, p. 4.

[3] *Histoire de l'Académie Royale des Sciences*, 1786 (printed 1788), p. 132.

[4] *Essay on Phlogiston and the Constitution of Acids*, 1787, p. 134.

[5] *Essai sur le Phlogistique traduit de l'Anglais de M. Kirwan, avec des Notes de MM. de Morveau, Lavoisier, de la Place, Monge, Berthollet, et de Fourcroy*, Paris, 1788.

to ascertain whether pure iron, steel, and cast iron contain the same amount of heat. He therefore attacks the materials with a solvent, and notes the heat evolved. He says the solvent breaks up the assemblage of the aggregation of molecules and forms other unions. If the new body demands more heat than the body which has been disunited, then the thermometer falls. If, on the other hand, the degree of heat required is less, the environment will be heated, which will result in the rise of the thermometer. In modern language, when a chemical compound is formed, heat is evolved and energy is lost, but if one substance, say a metal, simply dissolves another, the solution is attended with absorption of heat, and the product, when attacked by a suitable solvent, should evolve practically the same amount of heat, but certainly not less than would be evolved by the individual metals present in solution.[1] This is specially interesting from its relation to the calorimetric work of Lavoisier and Laplace in 1780, and of Lavoisier in 1782, which led him to explain the nature of oxidation, and to show that a metal could be as truly calcined or oxidised by the action of a solution as by the action of air at an elevated temperature. Now that the importance of thermal chemistry is beginning to be recognised in relation to industrial chemistry and metallurgy, it is to be hoped that Bergman's merits will be more fully considered. The main point is, that he taught that the difference between iron and steel consists in the $\frac{2}{10}$ to $1\frac{1}{2}$ per cent. of carbon which steel contains.

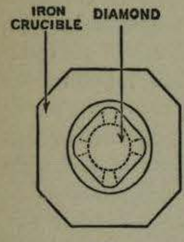

Fig. 44.

It was only natural that Black, writing in 1796, should have attributed the hardening of steel to the "extrication of latent heat," "the abatement of the hardness by the temper" being due, he says, "to the restoration of a part of that heat";[2] still he recognised that the work of Bergman had entirely changed the situation. The next step was made in France. It was considered necessary to establish the fact that carbon is really the element which gives steel its characteristic properties, and with this object in view Clouet,[3] in 1798, melted a little crucible of iron, weighing 57·8 grammes, containing a diamond, weighing 0·907 gramme, and obtained a fused mass of steel. Fig. 44 shows a plan of the iron crucible and diamond from the drawing in Guyton de Morveau's paper.

His experiment was repeated by many observers, but the results were open to doubt from the fact that furnace gases could always obtain access to the iron, and might, as well as the diamond, have yielded carbon to the iron. The carbon might have been presented to the iron in the form of a gas capable of yielding carbon, and this element would as surely have found its way into the steel.

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[1] See French translation of Bergman's work, Paris, 1783, p. 72.

[2] *Lectures on the Elements of Chemistry*, vol. ii. (1803), p. 505.

[3] Experiment described by Guyton de Morveau, *Ann. de Chim.*, vol. xxxi. (1799), p. 328.

Margueritte,[1] for instance, in 1865, repeated Clouet's experiment, and showed that although carburisation can be effected by simple contact of iron and carbon, it is nevertheless true that in the ordinary process of cementation the gas carbonic oxide plays an important part, which had until then been overlooked. The discovery of Graham,[2] in 1866, of the occlusion of carbonic oxide by iron, gave additional support to this theory.

The question, however, of the direct carburisation of iron by the diamond has never been doubted since 1815, when a working cutler, W. H. Pepys,[3] heated iron wire and diamond dust together and obtained steel, the heat being afforded by a powerful electric battery. The absorption of carbon in the diamond form by iron may be made clear by reference to the diagram (fig. 45), which represents a glass vessel, which may either be rendered vacuous or may be filled with an atmosphere of gas through the tube *d* An iron wire *b*, placed between the terminals of a battery *c c*′, is heated to redness, and remains glowing until it is touched by pure diamond dust, which is effected by raising the cup *a*. The iron combines with the diamond dust and fuses.

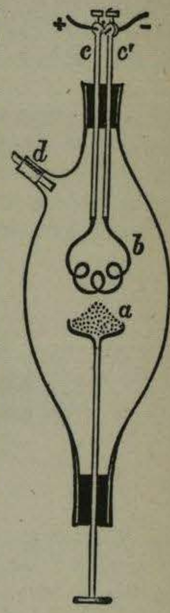

Fig. 45.

It must not be thought, however, that the steel owes its hardness to the passage of diamond into the iron *as diamond*. Margueritte's form of Clouet's experiment may be repeated by using a vacuum instead of an atmosphere of gas, and employing the form of apparatus shown in fig. 46, which represents an arrangement for heating the diamond and iron *in vacuo*. A strip of pure iron *b* is placed between two terminals *c c*′, which are connected with an electric supply. The vessel (of glass) is rendered vacuous by connecting the tube *d* with a Sprengel pump. The iron is then heated by an electric current and maintained glowing until all occluded gas is expelled from the iron, which is then allowed to cool *in vacuo*. Small, pure diamonds *a a*′ *a*″ are then placed on the strip of iron through the orifice into which the tube *d* fits. The vessel is rendered vacuous, and when the iron is again heated in contact with the diamonds it fuses and combines with them.

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[1] "*Sur l'aciération*," *Ann. Chim. et Phys.*, t. vi., 1865, p. 55.

[2] *Phil. Trans. Roy. Soc.*, 1866, pp. 399–439.

[3] *Ibid.*, 1815, p. 371.

The diamond by union with iron has passed, partially at least, to the other form of carbon, graphite; while treatment with a solvent which removes the iron shows that carbon has entered into intimate association with the iron, a fact which leads us to the next step in the study of the relations between carbon and iron.

Hempel[1] has shown that, in an atmosphere of nitrogen, solid iron appears to assimilate the diamond form of carbon more readily than either the graphitic or the amorphous forms, but directly carbon is associated with *molten* iron it behaves like the protean element it is, and the state which this carbon assumes is influenced by the rate of cooling of the molten mass, or even by the thermal treatment to which the solidified mass is subjected. As carbon is well known to exist in the distinctive forms of diamond, graphite, and soot, it need not be considered strange that carbon should be capable of being present in intimate association with iron, but in very varied forms.

The mode of existence of carbon in soft annealed steel is very different from that in which it occurs in hard steel. Karsten was the first to isolate, in 1827, from soft steel, a true compound of iron and carbon; Berthier[2] also separated from soft steel a carbide of iron, to which he assigned the formula FeC; and it need only be added that Sir F. Abel[3] gave much experimental evidence in favour of the existence in cold-rolled steel of a carbide, Fe_3C, which he isolated by the slow solvent action of a chromic acid solution. His work has been accepted as conclusive, and has been the starting-point of much that has followed.

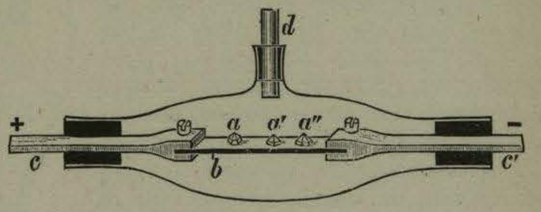

FIG. 46.

Obviously the microscope should reveal wide differences between the structure of various kinds of iron and steel; and the late Dr Sorby, in his very delicate investigations into the structure of steel,[4] has shown that this is the case, the point of main importance being the existence of a substance which Sorby called the "pearly constituent" in soft steel. This pearly constituent is closely related to the carbide of iron, Fe_3C, of Abel, and is a mechanical mixture of Fe_3C and pure iron. Its presence is diagrammatically indicated in fig. 47. The diagram will serve for the purpose of illustration to indicate the appearance when soft, hardened, and tempered steel are respectively treated with a solvent which acts gently on the mass.

The late M. Osmond prepared the following micro-sections of different varieties of steel expressly for this volume. The degree of carburisation varies from 0·45 to 1·60 per cent. of carbon, and the thermal treatment of the steel was in all cases different.

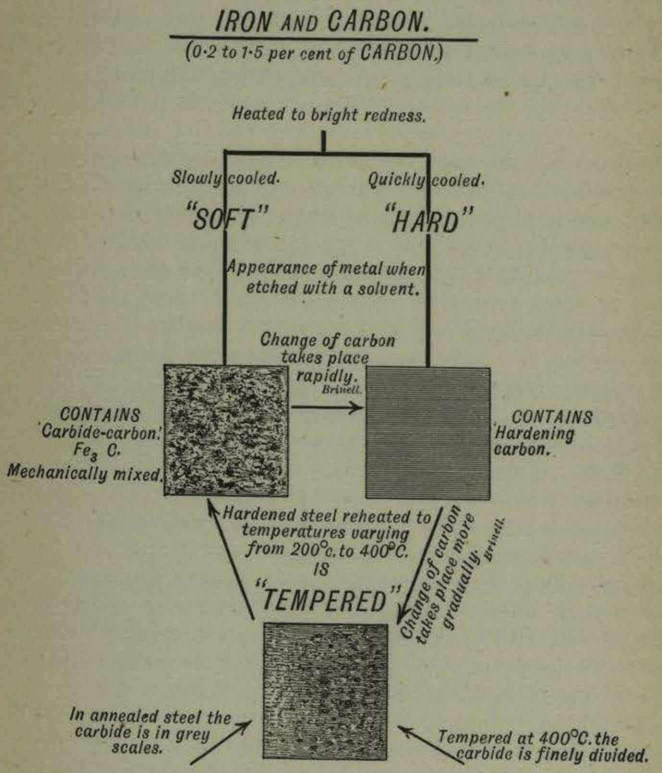

FIG. 47.

The method of preparing such micro-photographs is described on p. 213, and it must be remembered that the preparation and interpretation of such sections demands much experience. It is necessary to state at the outset that, in accordance with a suggestion made by Howe, mineralogical names have been given to the various constituents of steel, in order to facilitate their identification. For micrographic purposes steel is viewed as if it were a rock with various minerals distributed through it. Thus iron free from carbon is called *Ferrite*, and is left white and brilliant

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[1] *Ber. der. deutsch. chem. Gesellschaft*, vol. xviii. (1885), p. 998.
[2] *Ann. des Mines*, vol. iii. (1833), p. 229.
[3] *Proc. Inst. Mech. Eng.* (1883), p. 56.
[4] *Journ. Iron and Steel Inst.*, No. 1 (1887), p. 255.

when the polished specimen is treated with a solution of iodine or picric acid. Strong nitric acid also does not stain it, but the use of this reagent is not to be recommended to beginners in micrographic investigation.

Cementite, another constituent of steel, is a carbide which corresponds to the formula Fe_3C. It remains bright after the polished section of steel is attacked by iodine solution. It is hard, and stands in relief when the steel is polished with the finest rouge on parchment placed on a soft support such as wood.

Pearlite is an intimate mixture of ferrite and cementite; it is a very characteristic constituent of steel which has been slowly cooled from a high temperature, and if the steel contains 0·9 per cent. of carbon the mass will consist wholly of pearlite. It may be coloured dark by iodine solution, and its presence is best revealed when the steel is polished in relief by the method which has just been indicated, or treated with a 5 per cent. solution of picric acid in alcohol. Pearlite may exist in several conditions in steel, according to the rate at which the metal has cooled down; granular pearlite is obtained after fairly rapid cooling, laminated pearlite after very slow cooling, in which case the striæ are alternately hard and soft, and segregated pearlite after extremely slow cooling, in which case the parallel striæ disappear and the Fe_3C forms irregular massive segregations.

Martensite is the very hard micro-constituent of which hardened steel consists. It appears like a system of interlacing crystalline fibres. This structure is well developed by the *polish attack.* According to Sauveur, this consists of a solution of carbon in β iron.

Troostite,[1] according to Osmond, is an intermediate structure which occurs on the transformation of martensite into pearlite, and *vice versâ*. This is obtained on quenching specimens during the critical range of temperature; it is easily recognised on etching with HCl in alcohol (1 to 100), as it colours dark, while martensite remains unaffected. According to Sauveur, this consists of a solution of carbon in α iron.

Sorbite,[1] according to Osmond, is a transition structure which occurs between troostite and pearlite, but is now generally considered to be granular or sorbitic pearlite (emulsified pearlite of Arnold). It is obtained by cooling small samples in the air, or by quenching in molten lead.

Austenite is a constituent first identified by Osmond in high carbon steel which had been quenched from a high temperature in iced brine;[2] this has no well-defined structure, and is considered by Sauveur to be a solution of carbon in γ iron.

As M. Osmond pointed out, the two reagents, a solution of iodine or an infusion of liquorice, enable the micro-structures of steel to be divided into two groups, in both of which, however, martensite finds a place. These groups are (*a*) not coloured by infusion of liquorice—ferrite, cementite, and martensite; (*b*) coloured by liquorice—martensite, troostite, or sorbite. Martensite, which only assumes a yellowish tinge, may be recognised by its crystalline form. A dilute solution of iodine will, moreover, by acting on a polished surface, enable the structures to be again divided. Those which are not coloured by iodine are ferrite or cementite, while those which are coloured are sorbite, troostite, or martensite. These reagents, however, have been more or less superseded by such solutions as nitric or picric acids in alcohol; with the latter, the ferrite is not attacked or coloured, and the mottled appearance often caused by nitric acid is avoided. Le Chatelier uses a boiling alkaline solution of picric acid containing 25 per cent. NaOH and 2 per cent. picric acid to distinguish cementite from other constituents, this being the only one to be coloured by the solution.

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[1] See special note on page 161.

[2] *Comptes Rendus*, vol. cxxi., 1895, p. 684.

In order to distinguish troostitic and sorbitic structures from others, a freshly prepared solution of the following composition is used: 1 part of a 4 per cent. nitric acid solution in acetic anhydride is added to 3 parts of a solution made up of equal parts of methyl, ethyl, and iso-amyl alcohols. This solution colours only troostite and sorbite in ten minutes.

All the micro-sections of which the following photographs are given were magnified 1000 diameters. With the exception of fig. 52, they were all prepared by polishing and treatment with the infusion of liquorice. Fig. 52 was simply polished in relief on a soft base.

Figs. 48, 49, 50, 51 represent steel which contains 0·45 per cent. of carbon. Fig. 48 represents this variety of steel which has been forged and annealed at a temperature of 750°. It shows ferrite and pearlite, certain portions of the pearlite passing into sorbite. There are also a few grains of entangled slag. Fig. 49 shows the same variety of steel after it has been heated to 730° and quenched immediately in water. It contains troostite, ferrite, and martensite. Fig. 50 shows the structure produced by heating the same steel to 825°, allowing it to cool slowly from 825° to 720°, and then quenching it in water. The section after such treatment consists of martensite. Last, as regards this variety of steel, in fig. 51 the heating and quenching were effected at the same temperatures as in the case of fig. 50, but the steel was subsequently *tempered*, and the micro-section shows a confused structure without indicating the presence of definite constituents.

Figs. 52 and 53 were taken on micro-sections of steel which contain 1·24 to 1·5 per cent. of carbon. Fig. 52 consists mainly of pearlite. M. Osmond informed me that in the portion actually photographed the percentage of carbon probably fell below 1·24 per cent., as free cementite was absent, but it may be that the steel had not been cooled with sufficient slowness from a high temperature. In fig. 53, steel which has been cooled slowly, cementite and pearlite are both present.

Figs. 54 and 55 are very interesting. They represent steel containing from 1·5 to 1·6 per cent. of carbon—such a variety of steel, in fact, as would be produced by the ordinary operation of cementation. Fig. 54 represents a specimen which has been cooled in air, that is, more or less rapidly, but it has not been quenched, and contains cementite and sorbite, which in certain portions passes into pearlite, while fig. 55 has been heated and quenched at 1000° in iced water. It contains austenite and possibly some martensite. The austenite is the lighter constituent, the darker being probably martensite.

In all the cases represented in fig. 56 analysis would indicate the presence of precisely the same amount of carbon, 1·5 per cent. The series begins with a section revealing the structure of the metal when in the state of forged blister steel. This section is the circular disc in the centre of the series. In No. 1 the steel has been heated to 1000°, worked and slowly cooled. In it the carbide occurs in confluent masses, the groundwork being made up of alternate bands of iron and carbide, so that the structure resembles mother of pearl, the association being called "pearlite." In No. 2 the same steel has been heated to 850° and quickly cooled in air. The confluent masses have to some extent disappeared, and there is a groundwork of carbide in the distinct form, to which the name "sorbite" has been given. In No. 3 the same steel has been heated to 850° and quenched in water, and has thereby been "hardened," and the resulting structure is minutely acicular, the product being called "martensite." In No. 4 the interest deepens: the same steel has been heated to 1050°, and quenched, not in water, but in iced brine. The result is totally different from "martensite"; there are broad chevron-like bands of "martensite," enclosing lighter and much softer portions, to which the name of "austenite" was given by its distinguished discoverer, M. Osmond; but this result hardly prepares us for what happens when the steel is still further cooled by placing it in liquid air, thereby cooling it to −243°. The material, as No. 5 shows, swells up and becomes martensite or something very like it, forming a fern-like structure of singular beauty. In No. 6 the treatment has resulted in partial reversion to the original structure, but the metal has been quenched from a temperature near its melting-point, and what is known as a "burnt" steel is the product. No. 7 shows the result of annealing the original steel at a temperature of 650° for a long time, followed by slow cooling; the result is better developed bands of cementite, Fe$_3$C, and of the groundwork of pearlite, than in the specimen No. 1. Finally, by heating any of the specimens, except No. 6, to 850°, working them, and allowing them to cool slowly, the structure with

MICRO-SECTIONS OF DIFFERENT VARIETIES OF STEEL.

FIG. 48.—0·45 C. Steel. Annealed, showing Pearlite and Ferrite.

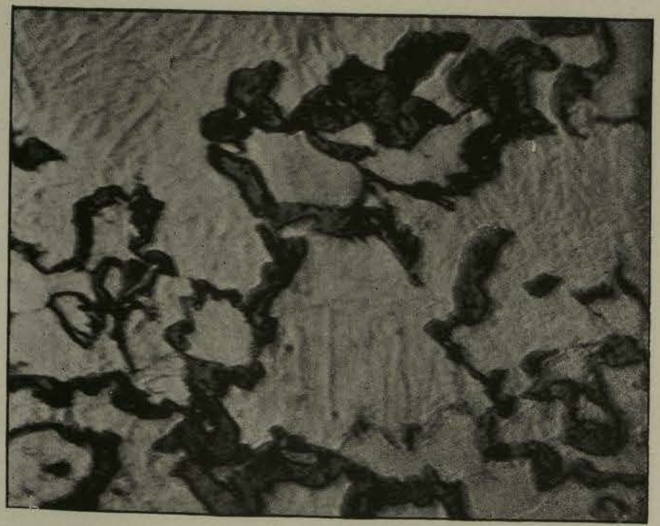

FIG. 49.—0·45 C. Steel. Quenched at 730° C., showing Troostite, Ferrite, and Martensite.

MICRO-SECTIONS OF DIFFERENT VARIETIES OF STEEL.

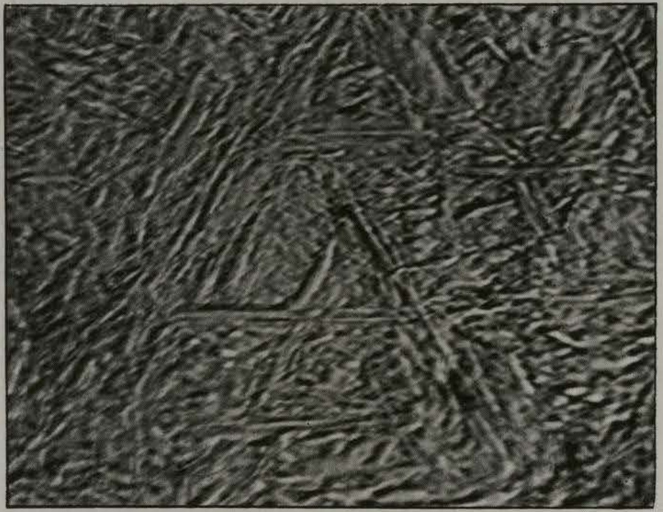

FIG. 50.—0·45 C. Steel. Quenched, showing Martensite.

FIG. 51.—Same as above, but tempered after quenching.

MICRO-SECTIONS OF DIFFERENT VARIETIES OF STEEL.

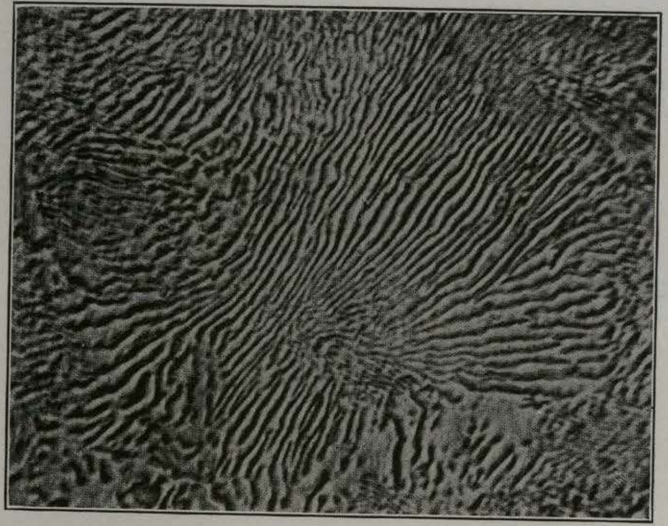

FIG. 52.—1·0 C. Steel, slowly cooled, showing Pearlite.

FIG. 53.—1·5 C. Steel, slowly cooled, showing Pearlite and Cementite.