MICRO-SECTIONS OF DIFFERENT VARIETIES OF STEEL.

FIG. 54 —1·5 C. Steel, cooled in air, showing Sorbitic Pearlite and Cementite.

FIG. 55.—1·5 C. Steel. Quenched at 1000° in iced water, showing Austenite and Martensite.

MICRO-SECTIONS OF STEEL.

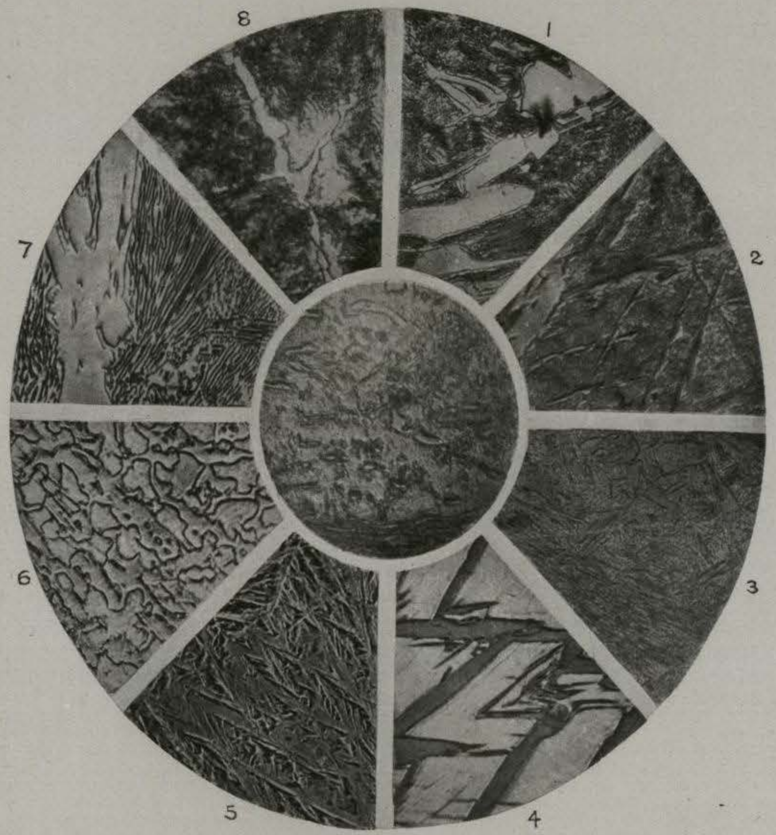

FIG. 56.—Structures of 1·5 C. Steel. Centre, Forged Blister Steel.

1. Heated to 1000°, worked and slowly cooled.
2. Heated to 850° and cooled in air.
3. Heated to 850° and quenched in water.
4. Heated to 1050° and quenched in iced brine.
5. Effect of liquid air on structure 4.
6. Quenched near melting-point.
7. Annealed at 650° and slowly cooled.
8. From any except No. 6. Heated to 850°, worked and slowly cooled.

which we started in No. 1 is practically again obtained, as shown by No. 8.

For convenience, the specimens have been arranged as segments of a circle round the section representing the original mass of "cement" steel. The point to be borne in mind is that these complex and varied molecular changes have occurred, except in the case of No. 6, in the solid, for in no other case has the steel been raised to a higher temperature than 1050°, which is more than 300° below its melting-point.

It will, I think, be evident that photo-micrography affords most important information as to the constitution of steel.

As regards the modes of existence of carbon, M. Osmond has arranged the following very useful table which shows the chemical properties of the different forms of carbon, other than graphite, which are met with in steel. It is the expression of a working hypothesis, fairly accounting for the facts which remain obscure in the chemical reactions of carbon in its various states. As M. Osmond[1] points out, this hypothesis admits, with Mr Sauveur, that there is a solution of carbide Fe_3C, which is at the same time the carbide of β iron of Mr Howe.

MODES OF EXISTENCE AND REACTIONS OF CARBON IN STEEL.

Description.			Formula.	Mode of occurrence in micro-section.	Results obtained by the respective methods of		
					Weyl.	Müller.	Eggertz.
Carbon, known as Cementation Carbon.	Cementite.	In fine plates.	$Fe\alpha_3C$.	Pearlite.	Set free.	Set free.	Soluble, with a brown coloration.
		Free (segregated)?	$Fe\beta_3C$.	Free (segregated)?	Give a carbohydrate.	Set free, with possibly a certain amount of loss.	Soluble, with a brown coloration.
		Dissolved.	$Fe\beta_3C$.	Martensite. Sorbite. Austenite.			
Carbon, known as Hardening Carbon.			C ions.	Martensite. Troostite?	Partially gasified.	Gasified.	Gasified.

Iron containing about 0·9 per cent. of carbon is, in fact, at the saturation point for steel; and when the concentration of the carbide reaches a certain point, in consequence of the separation of the constituents which are in excess, either the carbide or the iron is isolated simultaneously at a constant temperature, giving rise to the pearly constituent of Sorby. "Pearlite" is the *solid*

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[1] Discussion of a paper by Mr Sauveur, *Trans. American Inst. Mining Engineers*, Chicago meeting, Feb. 1897.

eutectic alloy of one of the forms of iron and of the carbide Fe_3C, and is generally called the "eutectoid," to distinguish it from ordinary eutectics, the nature of which is explained on p. 232. A study of the admirable work of Ledebur[1] and Campbell,[2] the latter of whom has studied the condition of carbon in steel from the point of view of the complex hydrocarbons which are liberated when the metal is treated with acids, will show how complex the relations of carbon and iron really are; but the question arises—Does a change in the "mode of existence" of carbon in iron sufficiently explain the main facts of hardening and tempering? It is possible to obtain by rapid cooling from a certain temperature, steel which is perfectly soft, although analysis proves that the carbon is present in the form which has been recognised as "hardening carbon." No doubt in the hardening of steel the carbon changes its mode of existence; but some other theory must be sought which will explain all the facts, and in order to do this it is necessary to turn to the behaviour of the iron itself.

In approaching this portion of the subject, a few elementary facts relative to the constitution of matter must be recalled, and in doing so a brief appeal to history must again be made. It is universally accepted that metals, like all elements, are composed of atoms of definite weights and volumes grouped in molecules. In order actually to transmute one metal into another it would be necessary to discover a method of attacking, not the molecule, but the *atom*, and of changing it, and this, so far as is known, has not yet been done; but it is possible, by influences which often appear to be very slight, to change the relations of the molecules to each other, and to alter the arrangement or distribution of the *atoms* within the molecules, and by varying, in this sense, the molecular arrangement of certain elements, they may be made to pass into states which are very different from those in which we ordinarily know them. Carbon, for instance, when free, or when associated with iron, may readily be changed from its diamond form to the graphitic state, though the converse change is much more difficult.

Sulphur, again, best known as a hard, brittle, yellow solid, may be prepared and maintained for a little time in the form of a brown viscous mass, but this latter form of sulphur soon passes spontaneously and slowly at the ordinary temperature, and instantaneously at 100°, to the solid octahedral yellow modification with evolution of heat. The viscous form of sulphur is an allotropic modification of that element. There are some well-known cases of allotropy in metals, and when they do occur they give rise to problems of vast industrial importance. Such

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[1] *Stahl und Eisen*, vol. viii. (1888), p. 742; and *Journ. Iron and Steel Inst.*, 1893, part ii.

[2] *Journ. Iron and Steel Inst.*, 1899, ii. p. 223.

molecular changes in metals are sometimes produced by the addition of a small quantity of foreign matter, and it would appear that the molecular change produced by the action of *traces* upon *masses* is a widespread principle of nature, and one which was recognised at the dawn of the science of chemistry, even in the seventh century, but distorted explanations were given of well-known facts, and gave rise to entirely false hopes. But students would do well to bear in mind that it is the same story now as in mediæval times; the single grain of powder which Raymond Lully said would transmute millions of its weight of lead into gold, the single grain of stone that Solomon Trismosin thought would secure perpetual youth, had their analogues in the small amount of plumbago which, to Bergman's astonishment, in the eighteenth century, converted iron into steel. By his time it was recognised that the right use of alchemy consisted in the application of its methods to industry, and we still wonder at the minuteness of the quantity of certain elements which can profoundly affect the properties of metals. The statements are true, and are not derived from poetical literature, early or late. There is no need to fear the taunt of Francis Bacon,[1] that "sottishly do the chymics appropriate the fancies and delights of poets in the transformation of bodies to the experiments of their furnaces"; for although it may not be possible to *transmute* metals, it is easy so to *transform* them by very slight influences that, as regards special service required from them they may behave either usefully or entirely prejudicially.

The question at once suggests itself—Can iron behave in a similar manner: is an allotropic form of iron known? Joule afforded experimental evidence for an affirmative answer to this question many years ago by communicating to the British Association in 1850 a paper on some amalgams. The result of his experiments, published in detail later,[2] in a paper which has been sadly neglected, showed that iron released from its amalgam with mercury is chemically active, as it combines readily with the oxygen of the air at the ordinary temperature, and he claims that the iron so set free is allotropic; but Joule did much more than this. Magnus has shown (1851) that the thermo-electric properties of hard and of soft steel and iron differ. Joule, in a paper on some thermo-electric properties of solids, incidentally shows that the generation of a thermo-electric current affords a method of ascertaining the degree of carburisation of iron, and he appeals to the "thermo-electricity of iron in different states" as presenting a "fresh illustration of the extraordinary physical changes produced in iron by its conversion into steel," and he adds the expression of the belief "that the excellence of the

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[1] Preface to the *Wisdom of the Ancients.*

[2] "On some Amalgams," *Mem. Lit. Phil. Soc. Manchester*, vol. ii. [3], p. 115.

latter metal might be tested by ascertaining the amount of change in thermo-electric condition which can be produced by the process of hardening."[1] It is by a thermo-electric method that the views as to the existence of iron in allotropic forms have been confirmed.

Jullien seems to have inclined to the view that iron is allotropic in his *théorie de la trempe*,[2] published in 1865, but he cannot be said to have done much beyond directing attention to the importance of hardening and tempering steel.

The next step was made in Russia in 1868. Chernoff showed that steel could not be hardened by rapid cooling until it had been heated to a definite temperature, to a degree of redness which he called α. Then, in 1873, Professor Tait[3] used this expression in a Rede Lecture delivered at Cambridge: "It seems as if iron becomes, as it were, a different metal on being raised above a certain temperature; this may possibly have some connection with the ferricum and ferrosum of the chemists." He also published his now well-known "first approximation to a thermo-electric diagram," which is of great interest in view of recent work. At about this time those specially interested in this question remembered that Gore[4] had shown that a curious molecular change could be produced by heating an iron wire. Barrett repeated Gore's experiment, and discovered that as an iron wire cools down it suddenly *glows*, a phenomenon to which he gave the name *recalescence*, and these investigations have been pursued and developed in other directions by many skilful experimenters.[5] In 1879 Wrightson called attention to the abnormal expansion of carburised iron at high temperatures.

The next point of special importance appears to be that recorded by Barus, who, by a thermo-electric method, showed, in an elaborate paper published in 1879,[6] that "the hardness of steel does not increase continuously with its temperature at the moment of sudden cooling, but at a point lying in the dark-red heat state" a maximum hardness may be attained by rapid cooling. Brief reference will again be made to the remarkable series of papers published by Barus and Strouhal,[1] embodying the results of laborious investigations, to which but scanty justice can be done here; and finally, in 1886, Pionchon[2] showed that at a temperature of 700° the specific heat of iron is altogether exceptional, and Le Chatelier[3] detected that at 700° a change occurs in the curve representing the electromotive force of iron, both experimenters concluding that they had obtained evidence of the passage of iron into an allotropic state. Osmond[4] then made the observations of Gore and Barrett the starting-point of a fresh inquiry. Bearing in mind the fact that molecular change in a body is always accompanied with evolution or absorption of heat, which is, indeed, the surest indication of the occurrence of molecular change, he studied, with the aid of a chronograph, what takes place during the slow cooling and the slow heating of masses of iron or steel, using as a thermometer to measure the temperature of the mass a thermo-electric couple of platinum, and of platinum containing 10 per cent. of rhodium, converting the indications of the galvanometer into temperatures by Tait's formulæ.

Figs. 57 and 58 show the actual mode of conducting the experiments. F, fig. 57, is a piece of steel into which a platinum and platinum-rhodium couple *t t′* is fixed. It is enclosed in a glazed porcelain tube, and heated to bright redness in the furnace

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[1] *Phil. Trans.*, vol. cxlix. (1859), p. 95.

[2] *Annexe au Traité de la Métallurgie du Fer*, 1865.

[3] *Nature*, vol. viii. (1873), pp. 86, 122; and *Trans. Roy. Soc. Edin.*, vol. xxvii. (1873), p. 125.

[4] Gore, *Proc. Roy. Soc.*, vol. xvii. (1869), p. 260. Barrett, *Phil. Mag.*, vol. xlvi. (1873), p. 472.

[5] G. Forbes, *Proc. Roy. Soc. Edin.*, vol. viii. (1874), p. 363. Norris, *Proc. Roy. Soc.*, vol. xxvi. (1877), p. 127. Tomlinson, *Phil. Mag.*, vol. xxiv. (1887), p. 256; vol. xxv. (1888), pp. 45, 103, and 372; vol. xxvi. (1888), p. 18. Newall, *ibid.*, vol. xxiv. (1887), p. 435; vol. xxv. (1888), p. 510. Fourth and Fifth Reports to Alloys Research Committee, *Proc. Inst. Mech. Eng.*, 1897, p. 31; 1899, p. 35. Carpenter and Keeling, *Journ. Iron and Steel Inst.*, 1904, i. p. 224. Rosenhain, *Proc. Physical Soc.*, 1907. Lambert, *Journ. Iron and Steel Inst.*, 1908, part i.

[6] Barus, *Phil. Mag.*, vol. viii. (1879), p. 341.

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[1] "Hardness (Temper), its Electrical and other Characteristics," Barus, *Phil. Mag.*, vol. vii. (1879), p. 341; *Wied. Ann.*, vol. vii. (1879), p. 383. Strouhal and Barus, *ibid.*, vol. xi. (1880), p. 930; *ibid.*, vol. xx. (1883), p. 525. "Hardness and Magnetisation," *ibid.*, vol. xx. (1883), pp. 537, 662. "Density and (Internal) Structure of Hard Steel and of Quenched Glass," Barus and Strouhal, *American Journ.*, vol. xxxi. (1886), p. 386; *ibid.*, p. 439; *ibid.*, p. 181. "Temper and Chemical Composition," *ibid.*, vol. xxxii. (1886), p. 276. "Temper and Viscosity," *ibid.*, p. 444; *ibid.*, vol. xxxiii. (1887), p. 20. Barus, *ibid.*, vol. xxxiv. (1887), p. 1; *ibid.*, p. 175. These papers, systematically discussed and enlarged, are embodied with new matter in the Bulletins of the United States Geological Survey—viz. *Bull.* No. 14 (1885), pp. 1–226; *Bull.* No. 27 (1886), pp. 30–61; *Bull.* No. 35 (1886), pp. 11–60; *Bull.* No. 42 (1887), pp. 98–131. The later literature of the subject is very voluminous. Arnold, *Proc. Inst. Civil Engineers*, vol. cxxiii. (1895–6), p. 127. Sauveur, *Trans. Am. Inst. Mining Engineers*, vol. for 1896. This paper was elaborately discussed at the subsequent meeting of the Institute in 1897. Le Chatelier, *Comptes Rendus*, cxxxvi. pp. 664–667. Demozay, *Journ. Iron and Steel Inst.*, 1907, iii. 144.

[2] *Comptes Rendus*, vol. cii. (1886), pp. 675 and 1454.

[3] *Ibid.*, vol. cii. p. 819.

[4] "Théorie cellulaire des Propriétés de l'Acier," *Ann. des Mines*, vol. viii. (1885), p. 5. *Transformations du Fer et du Carbone*, Paris, Baudoin et Cie., 1888. "Études Métallurgiques," *Ann. des Mines*, Juillet-Août, 1888. "Sur les nouveaux Procédé de Trempe," Mining and Metallurgical Congress, Paris, 1889; *Journ. Iron and Steel Inst.*, No. 1 (1890), p. 38. "On the Critical Points of Iron and Steel," *Journ. Iron and Steel Inst.*, 1890, i. p. 38; "Transformations allotropiques dans les Fers et Aciers," *Comptes Rendus*, vol. ciii. pp. 743 and 1135; vol. civ. p. 985; vol. cvi. p. 115; vol. cx. pp. 242, 346; vol. cxii. p. 578; vol. cxiii. p. 474; vol. cxviii. p. 532.

S (fig. 58). This tube T may be filled with any gaseous atmosphere. C is a bulb filled with chloride of calcium. The metal under examination is slowly cooled down. The wires from the thermo-couple pass to the galvanometer G. The rate of cooling of the mass, as indicated by the movement of a spot of light from the galvanometer mirror M, on the screen R, is recorded by a chronograph. The source of light is shown at L.

The curves given in the diagram, fig. 59, show how the rate of movement of the spot of light varies with different samples of steel. The stoppage of the movement of the spot of light of course indicates the evolution of heat from the cooling mass of steel F (fig. 57).

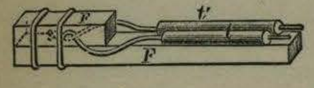

Fig. 57.

In fig. 59 the temperatures through which a slowly cooling mass of iron or steel passes are arranged along the horizontal line, and the intervals of time during which the mass falls through a definite number (6·6) of degrees of temperature are shown vertically by ordinates. See what happens while a mass of electro-deposited iron (shown by a dotted line), which is as pure as any iron can be, slowly cools down. From 1200° to 870° it falls uniformly at the rate of about 2·2° a second, and the intervals of temperature are plotted as dots at the middle of the successive points of the intervals. When the temperature falls down to 858° there is a sudden arrest in the fall of temperature; the indicating spot of light, instead of falling at a uniform rate of about 2° a second, suddenly takes 26 seconds to fall through an interval of temperature which hitherto and subsequently only occupies about 6 seconds. The diagram (fig. 59) shows what actually happens when the iron contains carbon in the proportion required to constitute it mild steel (indicated by a thin continuous line, fig. 59); there is not one, but there are two such breaks in the cooling, and both breaks occur at a different temperature from that at which the break in pure iron occurred. As the proportion of carbon increases in steel, the first break in cooling travels more and more to the right, and gradually becomes confounded with the second break, which, in steel containing much carbon, is of long duration, lasting as much as 76 seconds in the case of steel containing 1·25 per cent. of carbon (thick continuous line, fig. 59).

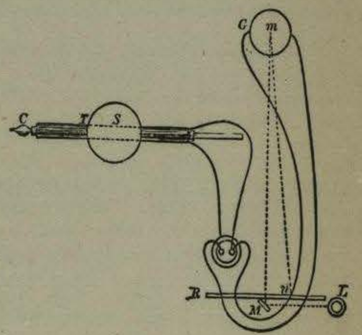

Fig. 58.

Now, it may be urged, as the presence of carbon has evidently an influence on the cooling of steel when left to itself, may it not affect molecular behaviour during the rapid cooling which is essential to the operation of hardening? It is known that the carbon during rapid cooling is retained in the state in which it is dissolved in the iron as carbide; it is also known that during slow cooling this dissolved carbide can separate itself from the iron so as to assume the form in which it occurs in soft steel. This second arrestation in the fall of the temperature corresponds to the recalescence of Barrett, and is caused by the reheating of the wire by the heat evolved when carbon leaves its state of solution and truly combines with the iron.

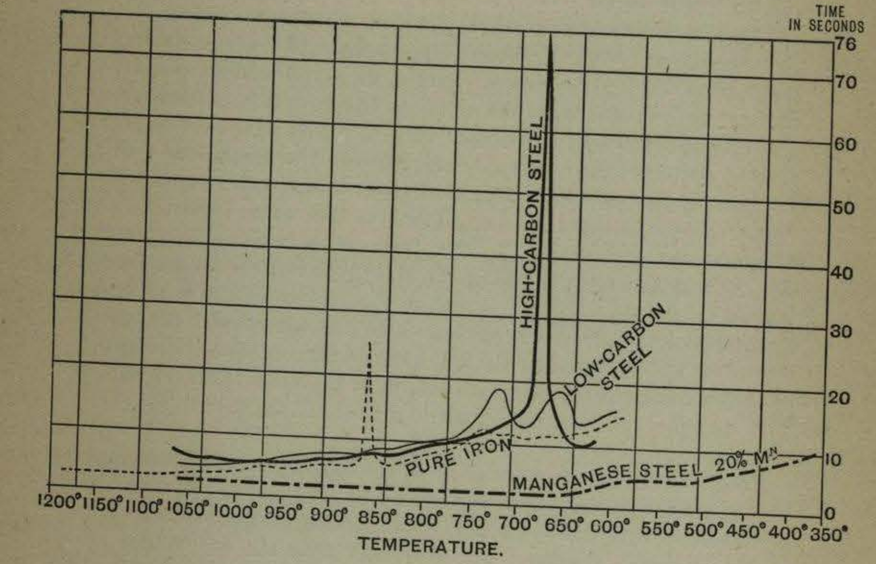

Fig. 59.

If it is hoped to *harden* steel, it must clearly be rapidly cooled before this combination of carbon and iron has taken place, or it will be too late to keep the carbon as hardening carbon. But what does the first break in the curves mean? It will be seen that it occurs in electrolytic iron, which is free from carbon; it must, then, indicate some molecular change in iron itself, accompanied with evolution of heat, a change with which carbon has nothing whatever to do, for no carbon is present, and Osmond argues thus:—There are two kinds of *iron*, the atoms of which are respectively arranged in the molecules so as to constitute *hard* and *soft iron*, quite apart from the presence or absence of carbon. In red-hot iron the mass may be soft, but the molecules are hard: let this be called β iron: cool such red-hot pure iron, whether quickly or slowly, and it becomes soft; it passes to the α soft modification, there is nothing to prevent its doing so. It appears, however, that if carbon is present, and the metal be rapidly cooled, the following result is obtained:—A certain proportion of the molecules are retained in the form in which they existed at a high temperature in the hard form, the β modification, and hard *steel* is the result.

In varieties of steel which contain less than 0·35 per cent. of carbon, there are three clearly shown main points of arrest in the cooling metal; and for these Osmond has given us a convenient notation: Ar, 3 occurs at 890°, Ar, 2 occurs at 760°, Ar, 1 occurs at 690°. (Round numbers have been given for the sake of clearness.)

There is, however, one other question of much importance to be considered. M. Osmond found that the appearance of magnetism in iron coincides exactly with the middle point in cooling-steel, that is, with the arrest in the evolution of heat from a cooling mass which is noted at 760° C. Now that it is demonstrated that the first arrest (about 890) and the second one (760) are independent, it seems clear that there must be three allotropic forms of iron instead of two—namely, the form α existing at temperatures below Ar, 2, the form β between Ar, 2 and Ar, 3, and the form γ above Ar, 3. What parts respectively played by β iron and by γ iron in the hardening of steel, and in the properties of manganese-steels and nickel-steels, have been indicated by M. Osmond in his contribution to the discussion of Mr Sauveur's paper to which reference has already been made.[1] The question is too complicated for brief discussion in this volume.

From the engineer's point of view, the most interesting information which the pyrometer (described on p. 176) has as yet afforded is connected with the detection of molecular changes which give rise to internal stresses. It is evident that the occurrence of molecular changes must be of vital importance when the metal is subjected at high temperatures to mechanical operations such as rolling or forging. The question naturally arises—Do the molecular changes in the iron take place at one moment throughout the mass of metal?—that is, is the rate of cooling approximately uniform throughout the mass? Or does the external portion of a hot ingot cool so much more rapidly than the centre as to allow the molecular changes in the iron, and the alterations in the relation between the carbon and the iron, to become complete near the surface long before they take place in the interior of the mass? The experimental difficulties in the way of obtaining information upon these points have hitherto appeared to be insuperable; but the pyrometric method used in this research, in conjunction with the evidence of photo-micrography, affords most important evidence, as a brief description of the following experiments will show.

If the steel be allowed to cool under pressure (the student must consult the original memoir[1] to see how this was effected), it will be found that the point of recalescence is lowered, as will be seen by reference to the curves (fig. 60).

The sample of steel contained 0·9 per cent. of carbon, and when cooled in air without pressure recalescence took place at close upon 690°. In two experiments shown, respectively dotted and continuous lines marked "30 tons per square inch," the point of recalescence was sensibly lowered by that amount of pressure. When the ingot was quenched in water the recalescence point fell to 300°. As regards the other source of evidence, sections taken from different parts of an ingot or forging show a gradual transition in the appearance of the micro-structure from the outer and quickly cooled portions to the inner and more slowly cooled portions.

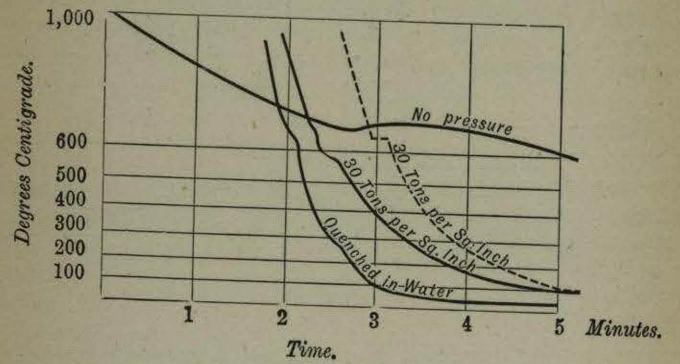

FIG. 60.

Barus[2] has pointed out that since most metals can be hardened by straining, it would follow that there should be α and β varieties in all cases, even though a molecular change corresponding to recalescence has only been observed in the case of a few metals. He believes, moreover, that there is reason to be urged in favour of this extreme view. This question has since received careful consideration by Howe.[3] The existence of molecular change in iron may be illustrated by the following experiment:—Take a bar of steel (fig. 61) containing much carbon. In such a variety of steel, the molecular change of the iron itself, and the change in the relations between the carbon and the iron, would occur at nearly the same moment. Heat this bar to red-

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[1] *Trans. American Mining Engineers*, Chicago meeting, 1897.

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[1] *Inst. Mech. Eng.*, part ii., 1893, p. 125.

[2] *Nature*, vol. xli. (1890), p. 369.

[3] *Journ. Iron and Steel Inst.*, 1895, ii. p. 258.

ness, one end of the red-hot bar being firmly fixed (fig. 61), and sling a weight *not sufficient to bend it* to the free end, which is lengthened by the addition of a reed to magnify any motion that may take place. As the bar is red-hot, it ought to be at its softest when it is freshly withdrawn from the furnace, and if the weight was ever to have power to bend it, it would be then; but, in spite of the rapidity with which such a thin bar cools down in the air and becomes rigid, points of molecular weakness come when the iron changes from β to α, and the carbon passes out of solution and forms carbide, Fe_3C; at that moment, at a temperature much below that at which it is withdrawn from the furnace, the bar will begin to bend. It has been found experimentally that this is the point at which, according to Osmond's theory, molecular change takes place. Coffin takes advantage of this fact to straighten distorted steel axles.[1]

Barus[2] traces the connection of this singular minimum of the viscosity of hot iron and the interpretation given of Maxwell's theory of viscosity, and he points out that "when iron passes through the temperature of recalescence, its molecular condition is for an instant almost chaotic. This has now been abundantly proved by Hopkinson. The number of unstable configurations, or, more clearly, the number of configurations made unstable because they are built up of disintegrating molecules, is therefore at a maximum. It follows that the viscosity of the metal must pass through a minimum. Physically considered, the case is entirely analogous to that of a glass-hard steel rod suddenly exposed to 300°. If all the molecules passed from Osmond's β state to his α state together, the iron or steel would necessarily be liquid. This extreme possibility is, however, at variance with the well-known principles of chemical kinetics. The ratio of stable to unstable configurations cannot at any instant be zero. Hence the minimum viscosity in question, however relatively low, may yet be large in value as compared with the liquid state."

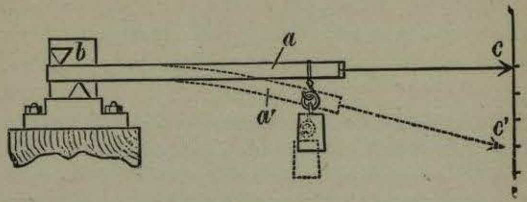

FIG. 61.

Sir W. Anderson urged his opinion that "when, by the agency of heat, molecular motion is raised to a pitch at which incipient

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[1] *Trans. American Soc. Civil Engineers*, vol. xvi. (1887), p. 324.

[2] *Nature*, vol. xli. (1890), p. 369.

fluidity is obtained, the particles of two pieces brought into contact will interpenetrate or diffuse into each other, the two pieces will unite into a homogeneous whole, and we can thus grasp the full meaning of the operation known as 'welding.'" It is, however, possible to obtain evidence of interchange of molecular motion, as has been so abundantly shown by Spring, even at the ordinary temperature, while in the case of steel it must take place far below incipient fluidity, indeed at a comparatively low temperature, as is shown by the following experiment on the welding of steel. Every smith knows how difficult it is to weld highly carburised hard tool steel, but if the ends of a newly fractured ¼-inch square steel rod *a* (fig. 62) are covered with platinum foil *b* so as to exclude the air, and if the junction is heated in the flame of a Bunsen burner *c*, the metal will weld, without pressure, so firmly that it is difficult to break it with the fingers, although the steel has not attained a red heat.[1]

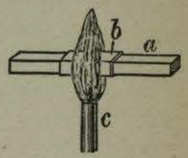

FIG. 62.

The question (partly considered in Chapter III.) now arises—What is the effect of the presence of other metals in steel? Take the case of manganese. This metal enables steel to harden very energetically, as is very well known. If much of it be present, 12 to 20 per cent., in iron, *no break whatever* is observed in the curve which represents slow cooling. (See line marked "Manganese Steel," fig. 59.) That is, the iron never shows such a change as that which occurs in other cooling masses of iron. Then such a material should be hard, however it is cooled. So it is. There is one other important point of evidence as to molecular change connected with the addition of manganese. Red-hot iron is not magnetic, and Hopkinson[2] showed in 1889 that the temperature of recalescence is that at which iron ceases to be magnetic. It may be urged that β iron cannot, therefore, be magnetised. Steel containing much manganese cannot be magnetised, and it is therefore fair to assume that the iron present is in the β form. Hadfield[3] has given metallurgists wonderful alloys of iron and manganese in proportions varying from 7 to 20 per cent. of manganese. Professor Ewing and others have specially examined the magnetic properties of this material, and Ewing concludes that "no magnetising force to which the metal is likely to be subjected, in any of its practical applications, would produce more than the most infinitesimal degree of magnetisation" in Hadfield's manganese steel. It has been seen that quantities of manganese above 7 per cent. appear to prevent the passage of β iron into the α form. In smaller quantities,

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[1] *Trans. American Soc. Mechanical Engineers*, vol. ix. (1888), p. 155.

[2] *Proc. Roy. Soc.*, vol. xlv. (1889), pp. 318, 455, and 457.

[3] *Proc. Inst. Civil Engineers*, vol. xciii., 1888, part iii. p. 1.

manganese seems merely to retard the conversion, and to bring the two loops of the diagram nearer together. With regard to the effect of other elements on steel, it need only be added that tungsten possesses the same property as manganese, but in a more marked degree. Chromium, on the contrary, enables the changes from hard β iron to soft α iron to occur at a higher temperature than would otherwise be the case, and this may explain the extreme hardness of chromium steels when hardened in the same way as ordinary steels.

The disappearance of the magnetic properties of iron on heating is of much interest in relation to the allotropism of the metal. Gilbert appears to have been the first to demonstrate, in his treatise *de Magnete*, published in 1600, that red-hot iron is not magnetic; and nearly half a century later Sir Thomas Browne,[1] with frequent reference to Gilbert's work, states that masses of iron, "by the fire, omit whatsoever they had received from the earth or loadstone," and he gives evidence of being aware that what is now called the "magnetic permeability" of iron and steel is affected by heating and cooling the metal. These facts have been recognised as being of vital importance in modern research, and they derive new interest from the sharp identification of the loss of magnetism with the temperature at which a molecular change in the iron takes place, and from Hopkinson's discovery that an alloy of iron with 25 per cent. of nickel is magnetisable if it be previously cooled (by solid carbonic anhydride) to a very low temperature.

Working of Steel.—There are a few considerations relative to the actual working of steel which can but briefly be dealt with, notwithstanding their industrial importance. The points *a* and *b* adopted in the celebrated memoir of Chernoff, the temperatures at which the carbon changes its state during heating and cooling respectively, change in position with the degree of carburisation of the metal. It is useless to attempt to harden steel by rapid cooling if it has fallen in temperature below the point (in the red) *a*, and this is the point of "recalescence" at which the carbon combines with the iron to form carbide carbon; it is called W by Brinell.[2] In highly carburised steel, it corresponds exactly with the point at which Osmond considers that iron, in cooling slowly, passes from the β to the α modification. Now with regard to the point *b* of Chernoff (or W of Brinell). If steel be heated to a temperature above *a*, but below *b*, it remains fine-grained, however slowly it is cooled. If the steel be heated above *b* and cooled, it assumes a crystalline granular structure whatever the rate of cooling may be. The size of the crystals, however, increases with the temperature to which the steel has been raised. The work

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[1] *Pseudodoxia Epidemica; or Enquiries into Vulgar Errors.* 2nd edition, 1650, p. 45.

[2] *Stahl und Eisen*, 1885.

both of Chernoff and of Brinell had for its object the determination of the relations between the thermal treatment condition of the carbon and the fracture. The importance of knowing exactly what is likely to occur by varying the thermal treatment has since received wide recognition. One result of this is that in working steel the "finishing" temperature is now carefully considered. In the case of steel rails, Mr Robert Hunt[1] of Chicago places the finishing temperature as low as 1580° F. (860° C.).

Now the crystalline structure, which is unfavourable to the steel from the point of view of its industrial use, may be broken up by the mechanical work of forging the hot mass; and the investigations of Abel, of Maitland, and of Noble have shown how important "work" on the metal is. When small pieces of steel are quenched in oil from a high temperature they are hardened, but to a less extent than if water be used as the cooling agent; this partial hardening has a toughening effect on the metal, and the tendency to brittleness is far less marked than in the case of water quenching.[2] If the mass of metal is large, such as a propeller shaft or tube of a large gun, the change in the relations between the carbon and the iron, or true "hardening," produced by such oil treatment, is only effected *superficially*, that is, the hardened layer does not penetrate to any considerable depth, but the innermost parts are cooled more quickly than they otherwise would have been, and the development of the crystals, which would have assumed serious proportions during slow cooling, is arrested. It depends on the size of the quenched mass whether the tenacity of the metal is or is not increased, but its power of being elongated is considerably augmented. This prevention of crystallisation probably constitutes the great merit of oil quenching, which, as regards large masses of metal, is certainly not a true hardening process.

The effect of annealing remains to be dealt with. In a very complicated steel casting, the cast metal probably contains some of its carbon as hardening carbon, and the mass, which has necessarily been poured into the mould at a high temperature, is more or less crystalline. The effect of annealing is to permit the carbon to pass from the "hardening" to the "carbide" form, and incidentally to break up the crystalline structure, and, perhaps a matter equally important from a practical point of view, to relieve the stress set up due to unequal cooling. The result is that the annealed casting is more reliable; a test bar taken will give a higher elongation under work stress than one from the original casting. It would obviously be impossible to "work"—that is, to hammer—complicated castings; and the extreme importance of obtaining a fine crystalline structure by annealing, with the

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[1] *Trans. Amer. Inst. Min. Eng.*, Feb. 1901.

[2] This was well shown in Prof. Akerman's celebrated paper on "Hardening Iron and Steel," *Journ. Iron and Steel Inst.*, 1879, part ii. p. 504.