TABLE LXII.—SHOWING DEFLECTION OF SPRINGS COMPRESSED UNDER VARYING LOAD.

Type		Length between Centres.	Number and Thickness of Plates.	Camber Unloaded.	Deflection, per ton.											Deflection, per ½ ton.											
					1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	·	5.	1.	1.5.	2.	2.5.	3.	3.5.	4.	4.5.	5.	5.5.	6.
Engine,	Bearing, ·	Ft. Ins. 2 10	Ft. Ins. In. 10 5 × ⅜	Ins. 2⅞	In. 1⁄16	1⁄16	1⁄16	1⁄16	1⁄16	1⁄16	1⁄16	1⁄16	1⁄16	1⁄16													
" bogie,	" ·	3 6	{ 4 5 × / 8 5 × }	4⅞																							
"	" ·	Timmis' spiral	{ 6 ins. dia., / 2 ins. hole }	12⅝ long																							
"	" ·	Spiral	6½ ins., 2⅜ ins.	12⅞ "																							
Carriage,	Bogie bearing,	Ft. Ins. 5 0	Ft. Ins. In. 9 3½ × ¼	Ins. 6																							
"	Buffing, ·	5 8		15																							
10-ton waggon,	Bearing, ·	3 9		6																							
7-ton "	" ·	3 9		7																							
Waggon, ·	Buffing, ·	5 11¾		14½																							
Horse-box,	Bearing, ·	4 0		3½																							

CHAPTER XV.

CARBON AND IRON.

THE mutual relations of Carbon and Iron is a subject which, until comparatively recent years, had not been systematically investigated. While the peculiar characteristics possessed by steel have been recognised from the very earliest times, yet the explanation of the phenomena of hardening, tempering, and annealing, constituted problems the solution of which became possible only by the higher development of more exact processes of chemical analysis, and investigation involving the application of technical skill of a high order. It was not until 1781 that the chief cause of the phenomena referred to was shown by the Swedish chemist Bergman to be the presence in steel of varying, though small, amounts of Carbon.

Many and varied were the recipes of early writers for the treatment of steel, but all knowledge of the subject was empirical, the nature of the fluid employed for quenching being regarded as the secret to successful treatment. The constitution and behaviour of steel formed a wide field for the speculations of supporters of the doctrine of Phlogiston, and the eminent chemist Stahl, while recognising the essential identity of iron and steel, held the belief that the difference lay solely in the relative richness of the latter in Phlogiston. The developments of physical chemistry have led us to regard changes occurring in solid matter, such as steel, as due to molecular disturbances.

These modern views were foreshadowed in a remarkable manner by Reaumur, who regarded steel as containing in its molecules Sulphurs and Salts which by heating were driven out from the molecules into the interstitial spaces, and that by sudden cooling the particular conditions existing at any temperature were preserved. Bergman, to whom reference has already been made as having established the fact that steel differs from iron in containing small amounts of Carbon, also conceived the possibility of the iron itself being allotropic at different temperatures. Although anticipating in a remarkable manner the views of modern workers, as will be shown later, Bergman seems to have been influenced, in common with other writers of this period, by the necessity of adhering to the conception of Phlogiston.

The Direct Combination of Iron and Carbon.—The verification of Bergman's statement with respect to iron and Carbon quickly followed when Clouet, as pointed out by Sir W. Roberts-Austen, melted a small iron crucible containing a diamond and obtained as the result a fused mass of steel. The question of the possible effect of furnace gases was eliminated by Pepys, who, in 1815, heated iron wire with diamond dust in vacuo, while later Clouet's experiment has been repeated by Sir W. Roberts-Austen, who used electrolytic iron and performed the operation in vacuo. As to the possibility of direct carburisation of the iron there can be no doubt, but it would seem, as the result of this experiment, that combination does not take place until a full red heat is reached. This disposes of the assumption made by Le Play and early writers that the cementation of iron necessarily involves the action of Carbonic Oxide, and shows that Carbon may diffuse into and combine directly with iron.

Limits to the Amount of Carbon taken up by Iron.—In the molten state, *pure* iron is capable of dissolving up to about 7 per cent. of Carbon, but on solidification only 2 per cent. is held in solution, and in alloys containing more than 2 per cent. the excess over this separates on solidification. The total amount of Carbon, however, retained on soldifica-tion depends in a great measure on the purity of the alloy ; and the presence in any considerable quantity of other elements, such as Manganese, may greatly increase the amount of Carbon retained.

Condition of Carbon in Iron.—The earliest evidence as to the condition in which Carbon exists in iron was that adduced by Faraday, who, in 1822, established the fact that at least two different conditions existed in quenched and annealed steel respectively, the former dissolving completely in dilute Hydrochloric Acid while the latter left a carbonaceous residue. Caron*·worked on similar lines, and showed that rolled steel gave a larger amount of carbonaceous residue than hammered, and stated that the amount obtainable was proportional to the time of annealing. Rinman, in 1865, proposed to assign names to the two forms of Carbon existing respectively in quenched and worked steel, and in blister and unworked (annealed) steel. To the first he gave the name "hardening" Carbon, and to the second "cement" Carbon. Karsten also recognised these forms, and also Graphite. He regarded cement Carbon as a Poly-carbide of Iron. This idea of the existence of Carbides of Iron has long prevailed in the minds of chemists. Berthier was of the opinion that a Carbide, FeC, existed, while Berzelius believed in the existence of Carbides FeC_2 and Fe_2C_3.

Karsten, moreover, supposed the condition of the Carbon in hardened steel to be identical with the Polycarbides of white iron. The existence of a definite Carbide of Iron in annealed steel and white iron was first established by Abel, who, by means of Chromic Acid solutions, isolated a Carbide of the general composition Fe_3C.

Müller obtained a residue from Bessemer steel which was pyrophoric. Following this came work on the thermal effects produced by dissolving in acid, steels differently treated, with a view to determining whether this would throw any light on the Carbon condition. In annealed and hardened steels it was shown that the higher the Carbon percentage the less was the amount of heat evolved on solution, and hence it is to be supposed that the separation of the Carbon from the iron results in an absorption of heat.

In the hardened state more heat is evolved than in the annealed con-dition, but in considering the Carbon in steel which has been cold-worked, difficulties arise. Abel has shown that cold-working does not produce hardening Carbon, although the amount of heat evolved is nearly as great as in case of quenched steels ; in the case of cold forged steel the heat evolved is the same for steels containing ·17 or ·54 per cent. of Carbon, which seems to show that no relation exists between the total percentage of Carbon and the heat evolved.

It is possible that Carbon may exist in steel in various forms and com-binations, but Graphitic Carbon, Cement Carbon, and Hardening Carbon are accepted by all metallurgists.

Graphitic Carbon.—This is comparatively rarely found in steels, and then in small quantities only, and is confined almost entirely to cast iron. When molten iron has taken up more carbon than the solidified metal is able to retain, the excess is found as Graphite on the metal solidifying. It is attacked neither by boiling Hydrochloric nor by Nitric Acid (sp. gr. 1·20).

* Percy's *Metallurgy*.

Cement Carbon.—This is the Fe_3C first isolated by Abel, by dissolving steel in a Sulphuric Acid solution of Bichromate of Potash.* It has long been recognised as existing in *unhardened steels*, and as being left insoluble on dissolving the steel in certain dilute acids. This is the same as the cement Carbon of Rinman, although it was left for Abel to prove that it was a definite Carbide.

With weak Hydrochloric or Sulphuric Acid, the Carbide remains in the form of a grey-black powder. On heating in Nitric Acid of 1·18 to 1·2 specific gravity, this form of Carbon dissolves, imparting a brown colour to the iron solution—a reaction used in the well-known Eggertz colour-test for the determination of Carbon. This Carbide separates from solution during the slow cooling of Carbon steels, its separation being accompanied by an evolution of heat.

Arnold and Read† have separated this Carbide by an electrolytic method.

Hardening Carbon.—This form of Carbon escapes as a Hydrocarbon with an unpleasant smell, even at the ordinary temperature, if the steel is dissolved in dilute Sulphuric or Hydrochloric Acid. When dissolved in cold Nitric Acid, the hardening Carbon remains as a black residue, which, on gentle heating, rapidly dissolves, and, on stronger heating—to 100° C.—escapes as a gas, as was originally shown by Osmond and Werth. This hardening Carbon is almost completely soluble in the chromic solvent of Abel. It is found in quenched steels, and the hardness, brittleness, and tenacity of the steel increase with the percentage of this hardening Carbon, but diminish again when the percentage passes a certain limit. The more rapid the cooling of the steel the larger is the percentage of hardening Carbon found, but, according to Ledebur,‡ on reheating the steel to as low a tem-perature as 200° C., the iron Carbon alloy commences to slightly decompose with the formation of Fe_3C and iron, and the higher the temperature is raised the more marked does this transformation become.

Temper Carbon.—Professor Ledebur recognises another modifica-tion of Carbon, which he has called temper Carbon, describing it as greatly resembling, but distinct from, Graphite. It takes its name from the fact that it is mainly formed during the prolonged heating of white pig-iron during the tempering or annealing process. In steel that contains upward of 1 per cent. of Carbon, and has been heated to redness, this form of Carbon may be observed. When the iron is dissolved in acids, the temper Carbon behaves exactly like Graphite—that is to say, it is not attacked by boiling Hydro-chloric or Nitric Acid. The temper Carbon differs, however, from Graphite by its amorphous condition, and still more in that when the iron is heated under oxidising conditions (for instance, in contact with iron ore, as in the manufacture of malleable castings), it somewhat rapidly disappears, even when it occurs, not on the surface, but in the interior, of the iron mass, whilst Graphite remains unaffected by this treatment. The existence, however, of this form of Carbon has not been confirmed by other investigators, and the general opinion appears to be that it is really modified Graphite with special physical properties.

Professor Arnold has, in conjunction with Mr. Read, very carefully studied the question of the mode of combination of Carbon in steel. The

* *Iron*, 1883, vol. i., p. 76 ; and 1885, vol. i., p. 115.
† *Journal Chem. Soc.*, Aug., 1894.
‡ *Iron and Steel Inst. Journ.*, 1893, vol. ii., p. 60.

following are the results they arrived at, as detailed in a paper read before the Chemical Society *:—

(1) "That the existence of a Carbide of iron possessing the formula Fe_3C, as discovered by Abel and Müller by independent methods, is fully confirmed."

(2) "That the normal Carbide exists in two forms identical in chemical composition—(a) a diffused Carbide scattered in microscopic granules, or very small plates, throughout the iron in normal steel, yielding, on isolation, a greyish-black powder; (b) a crystalline Carbide arranged in comparatively large distinct plates in well-annealed steel: these plates, which occur chiefly in the form of well-marked striæ, consist of almost chemically pure Fe_3C, are identical with the microscopical laminæ of Dr. Sorby's 'pearly constituent,' and yield, when isolated, bright silver plates."

(3) "That the percentage of the total Carbon obtained as Carbide is greater in hard than in mild steel, the yield being, in normal numbers, as follows:—

For iron containing 1·00 per cent. C, 92 per cent. ; loss, 8 per cent.
  "   "   0·50   "   87   "   "   13   "
  "   "   0·25   "   74   "   "   26   "   ."

(4) "That the above loss does not appear to be due to decomposition, but rather to the presence of an unstable sub-Carbide of iron (containing less Carbon than the normal compound), existing to the extent of about 25 per cent. of the total Carbon in mild steel, and capable also of existing to the same extent in hard steel, after the latter has been heated for some time at a white heat."

(5) "That the loss being practically the same in well-annealed steel as in the normal metal, it cannot be due, as supposed by Ledebur, to the presence of hardening Carbon."

(6) "That the Carbon in hardened steel exists as a feebly combined and extremely attenuated Carbide, leaving, on isolation, a residue consisting mainly of Hydrate of Carbon, mixed to a slight extent with normal Carbide of iron. Whether the large loss of Carbon (about 50 per cent. of the total) occurring during the galvanic decomposition of hardened steel is due to the presence of a large percentage of sub-Carbide, or to evolved Hydrocarbons formed by the action of nascent Hydrogen on finely-divided, free, or feebly combined Carbon, there is no conclusive evidence to show, although the evolution of gas from hardened steel does not perceptibly exceed that from unhardened samples."

(7) "That in steel high in Manganese a portion of the iron may be replaced by Manganese, and that the double Carbide is less stable than that of iron alone, especially in normal steels."

In a paper read before the Iron and Steel Institute by Messrs. E. D. Campbell and M. B. Kennedy† some interesting results are given on the separation of Carbides from annealed white iron. From very pure white iron which had been subjected to long annealing the authors obtained, on dissolving the iron by electrolysis, a Carbide residue which could be separated by mechanical sifting into a coarse and a fine portion. The former contained less Carbon than the latter, and although varying somewhat in analysis approximated to the formula, Fe_3C, while the latter gave results corresponding nearly to the formula, Fe_2C. The chemical behaviour of the two Carbides was almost identical, but Fe_2C seemed to be less soluble in Potassium Cupric Chloride and Hydrochloric Acid than the Fe_3C, although not to a marked extent. The authors are of opinion

* Journal of the Chemical Society, vol. lxv., p. 788, 1894.
† Iron and Steel Inst. Journ., 1902, vol. ii.

that they have isolated two Carbides, Fe_2C and Fe_3C, but that the molecular formula is some multiple of these, and may be expressed by the general formulæ, $(Fe_2C)_n$ and $(Fe_3C)_n$.

Although the different conditions under which Carbon exists in steel are still disputed points, the effects of different percentages of Carbon on the physical properties of steel, and the influence they exert, either directly or indirectly, when the steel is subjected to different heat treatment, have now been fairly well demonstrated. Whether these physical changes are due to the Carbon *per se*, or whether they are due to some allotropic change in the iron itself, induced by the presence of Carbon, does not concern us at the present moment, as the facts are the same whatever the cause, and it is these alone we have now to consider.

Influence on Physical Properties.—When a bar of steel containing less than about ·15 per cent. of Carbon is quenched in water from a full red heat there is no very appreciable hardening of the bar, as shown by an ordinary bend test,* but in the case of steels containing over ·2 per cent. of Carbon, the hardening by rapid cooling at once becomes apparent, and increases with the percentage of Carbon present, at all events up to about 1 per cent. This is so well known that it has always been customary since the manufacture of steel became an established industry, to grade the steels according to their Carbon content, and we are thus enabled to select steels of varying degrees of hardness for different purposes, such as chisels, dies, saws, springs, files, razors, &c. The degree of hardness conferred on any grade of steel will vary with the temperature from which the steel is quenched or cooled and the rapidity of quenching, and by varying these, very different results may be obtained. Thus, if the highest degree of hardness is required for a medium Carbon steel, it is obtained by quenching from a full red heat in mercury or iced brine, while quenching in hot water, oil, or molten lead would have a much less hardening effect. For most purposes the hardness induced by rapid cooling in water or oil is too great, as with the hardness the brittleness of the material increases, and it is necessary to modify this by reheating to certain definite temperatures. This is called tempering, and may be regarded as regulating or modifying the hardness conferred by quenching, to suit the purpose required; it is known in practice as "letting down" the steel. It reduces the brittleness and increases the toughness and elasticity of the material, and by thus reheating hardened steel to different temperatures, different degrees of hardness may be obtained. When a bar of bright steel is gradually heated in air, series of colours appear successively on the surface, first a light straw colour, then dark straw, gold, brown, purple, light blue, deep blue, and finally black. These colours are oxidation films, and indicate very accurately successive changes in the temperature of the steel, and enable the practical man to reduce or regulate the hardness of a quenched steel by stopping the heating at any required point. The particular point to which the heating should be carried depends upon the purpose for which the steel is required, different tools requiring different degrees of tempering. The following table for tempering is given by Metcalf † :—

Light straw to straw,	For lathe tools, files, &c.
Light brown (gold) to dark brown,	" taps, reamers, drills, &c.
Pigeon-wing (purple),	" axes, hatchets, and drills.
Light blue,	" springs.
Dark blue,	" some springs (seldom used).

* The hardening of carbonless steel is referred to on p. 362.
† Manual for Steel Users, p. 117.

These particular colours for the given purposes are simply those which have been arrived at as the result of experience, and have been found broadly to give the best practical results; but different workmen will vary the "tempering" to suit their special conditions. The word temper, when used as a verb, always means this modifying of the hardness, but as a noun it is frequently used in a different sense, to indicate the grade of the steel. Thus when a steel is spoken of as high, low, or medium temper, it does not mean that it has been tempered at a high, low, or medium temperature, or that it is of a certain degree of hardness, but that it is a high, low, or medium Carbon steel, and is a steel *capable* of taking a high, low, or medium degree of hardness in quenching. Thus 1·5 Carbon steel would be spoken of as high temper, and ·3 Carbon as low temper. On the other hand, when a steel is said to have taken a certain "temper," it means that it is hardened to a definite extent. It is important to bear these distinctive meanings in mind, as, otherwise, they are liable to lead to confusion.

In hardening and tempering, the steel to be operated upon should be carefully and uniformly heated to a red heat (about 850° C.), and quenched in water. The surface is then filed bright, and carefully and gradually heated on a hot iron plate, the surface of molten lead, a fusible alloy, or in any other convenient way, until the surface coloration indicates that the required temperature has been reached, when the material must be removed immediately and either immersed in water or oil, or allowed to cool in the air. In many cases where the whole of the metal is required of the same degree of hardness air cooling is quite satisfactory, but in cases where only the cutting part of a tool requires tempering it is not unusual to quench the cutting edge and temper it by the heat conducted from the unquenched end: in this case, directly the cutting edge shows the required colour, the whole tool must be quenched, as otherwise the heat from the hot end will continue to flow and will make the cutting edge too soft. It is this property which Carbon steel possesses of hardening and tempering which distinguishes it from wrought iron and from very mild steel.

Influence on Tensile Strength.

The influence of different percentages of Carbon on the tensile strength and other physical properties of steel, is a question which has been the subject of investigation by various metallurgists. In 1895 Professor Arnold* gave the results of a very complete research on a set of extremely pure steels varying from ·08 per cent. Carbon to 1·47. The author repeated these experiments on a similar set of pure steels under somewhat different conditions as to heat treatment, and, so far as the general mechanical effects are concerned, confirmed Arnold's results. Below are given the analyses of both sets of steels with the tensile tests, and for comparison the tenacity and elongation curves are shown diagrammatically together on the two diagrams (figs. 248 and 249). It will be seen that the general character of the tenacity curves is very similar, the maximum stress in the case of the author's bars being reached at a somewhat lower point, about 1 per cent. Carbon, as against 1·2 in the Arnold curve. This is accounted for, however, by the somewhat slower cooling to which the former annealed bars were subjected. In considering these curves the author's bars, annealed at 900° C. for thirty minutes and slowly cooled, must be compared with Professor Arnold's normal bars heated to 1,000° and cooled in air; and the author's soaked bars, heated for twelve hours and slowly cooled, with Professor Arnold's annealed bars, heated for seventy-two hours at 1,000° C. and slowly cooled. Professor Arnold's

* "Influence of Carbon on Iron," *Min. Proc. Inst. Civil Engineers*, vol. cxxiii., 1895-96.

normalising conditions correspond nearly to the author's annealing, and his annealing to the author's twelve-hour heating. The elongation curves are very similar in general character, the variations being such as might be expected from the difference in the temperature, time of heating, and composition of the steels.

We may therefore take it as established that the tensile strength of pure Carbon steels will vary from about 19 tons in case of ·08 Carbon steel to about 53 tons with 1 per cent. Carbon, and above this point the tenacity will vary somewhat till 1·2 per cent. Carbon is reached, in some cases giving as much as 61 tons and in others less than 50 tons per square inch, according to the temperature to which they have been heated. This applies
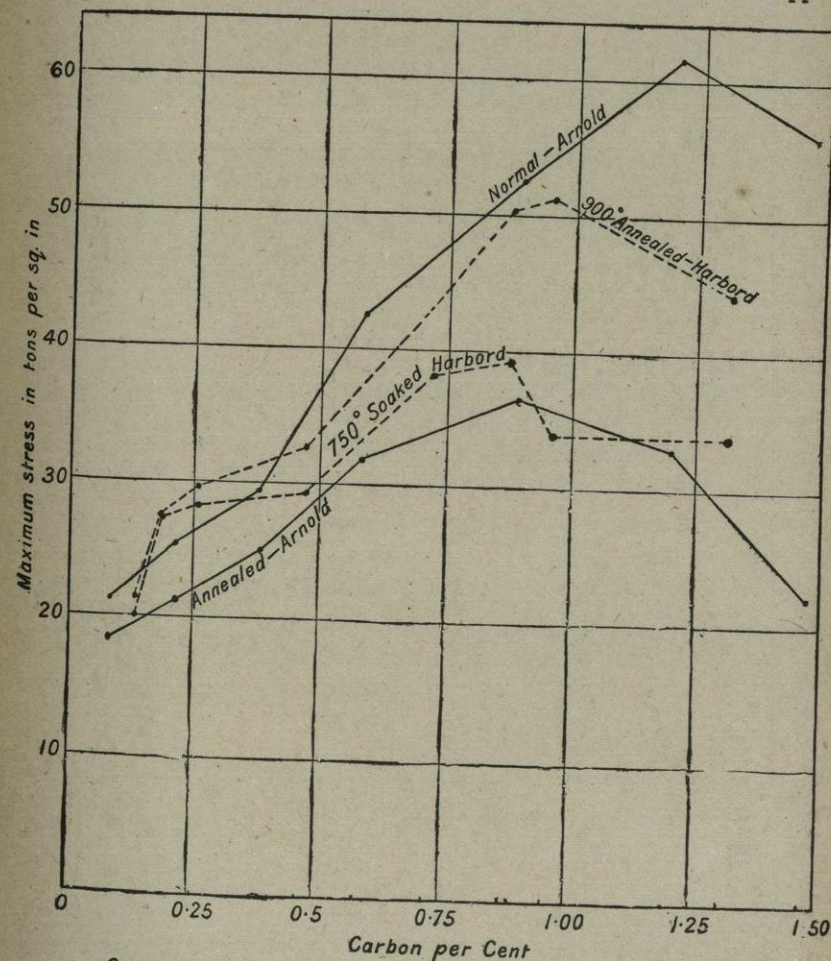
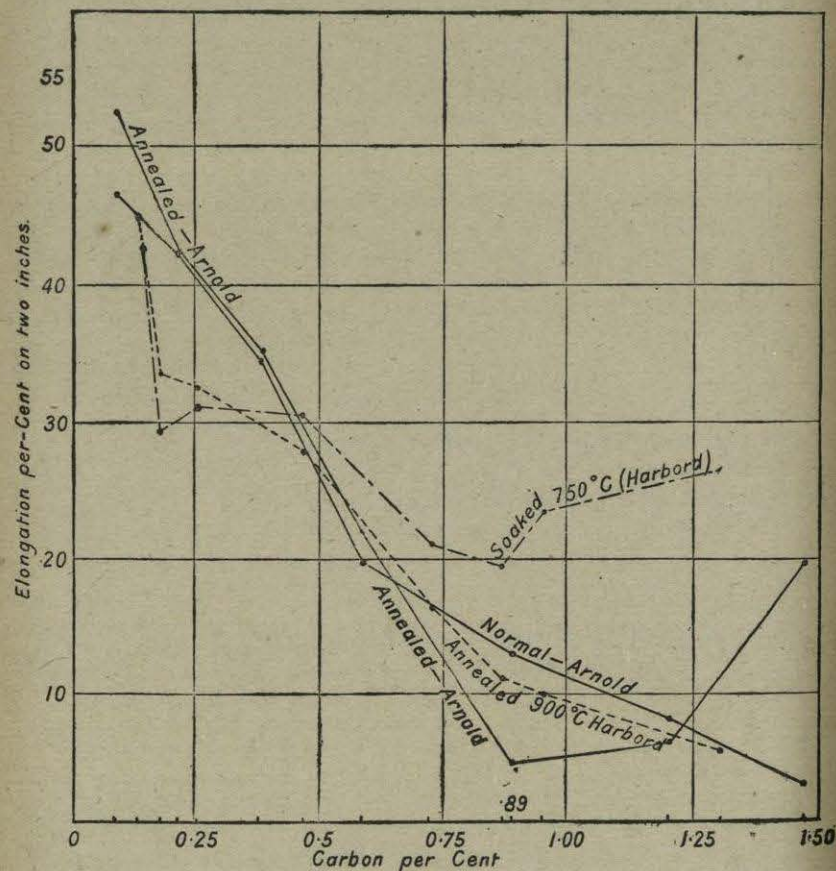Curves showing the influence of Carbon on tenacity of Steels

Fig. 248.

Arnold-normal	= heated 1,000° C. cooled in air.
" -annealed	= " 1,000° C. (72 hours) cooled in furnace.
Harbord "	= " 900° C. (30 minutes) " "
" -soaked	= " 750° C. (12 hours) " "

Arnold's normal bars comparable with Harbord's annealed bars, and Arnold's annealed bars with Harbord's soaked bars.

to steels that have been heated only sufficiently long to remove the strains due to mechanical work. The elongation gradually decreases as the Carbon increases from about 45 per cent. in ·08 Carbon steel to about 3 or 4 per cent. in case of 1·5 Carbon steel.

The effect of heating, broadly speaking, is to lower the tenacity and increase the ductility, but the results obtained vary with the heat treatment, and this will be more fully dealt with in Chap. xviii. on Heat Treatment. In the curves of steels which have been subjected to prolonged heating, both in Professor Arnold's and in the author's results, there is a very

Fig. 249.—Normal Arnold curve comparable with annealed curve, Harbord; and Arnold annealed curve with soaked curve, Harbord.

noticeable point between ·87 and 1 per cent. of Carbon at which the maximum stress is attained.

In the elongation curve there is also a break, as up to this point the ductility has been gradually decreasing, when it suddenly begins very slightly to increase again, and goes on steadily increasing until 1·5 per cent. Carbon is reached. These changes in mechanical properties correspond to a very definite change in microscopical structure, as when steel

contains ·89 per cent. of Carbon it is found to consist entirely of Pearlite,[*] and this point has been called by Professor Arnold the saturation point. If the percentage of Carbon is increased the Micro-constituent, Cementite, separates out, and if the Carbon is decreased free Ferrite appears.

Professor Arnold's Results. Normal Bars.

TABLE LXIII.—TENSILE TESTS OF BARS HEATED TO ABOUT 1,000° C. AND ALLOWED TO COOL IN AIR.

Steel No.	Total Carbon.	Graphite in Annealed Sample.	Silicon.	Manganese.	Phosphorus.	Sulphur.	Aluminium.	Tons per Square Inch.	Lbs. per Square Inch.	Tons per Square Inch.	Lbs. per Square Inch.	Elongation per Cent.	Reduction of Area per Cent.	Fracture.
			Analyses.					Elastic Limit.		Maximum Stress.				
1a	0·08	...	0·03	0·02	0·02	0·03	0·02	12·19	27,300	21·39	47,920	46·6	74·8	Grey granular silky edges.
1½a	0·21	...	0·05	0·05	0·02	0·03	0·02	17·08	38,270	25·39	56,860	42·1	67·8	,, ,,
2a	0·38	...	0·03	0·08	0·02	0·02	0·03	17·95	40,200	29·94	67,080	34·5	56·3	,, ,,
3a	0·59	...	0·07	0·10	0·02	0·02	0·03	19·82	44,400	42·82	95,920	19·9	22·7	Crystalline.
4b	0·89	...	0·03	0·09	0·02	0·02	0·03	24·80	55,550	52·40	117,150	13·0	15·4	,,
5b	1·20	0·28	0·07	0·15	0·02	0·02	0·03	35·72	80,000	61·65	138,100	8·0	7·8	,,
6b	1·47	1·14	0·08	0·13	0·02	0·01	0·04	32·27	72,300	55·71	124,800	2·8	3·3	,,

a, Average of two tests. b, Average of three tests.

Author's Results. Annealed.

TABLE LXIV.—HEATED TO A TEMPERATURE OF 900° FOR 30 MINUTES AND ALLOWED TO COOL SLOWLY IN MUFFLE.

Steel No.	Total Carbon.	Silicon.	Manganese.	Phosphorus.	Sulphur.	Tons per Sq. In.	Lbs. per Sq. In.	Tons per Sq. In.	Lbs. per Sq. In.	Elongation per cent. on 2 Ins.	Reduction of Area per cent.	Remarks.
		Analyses.				Elastic Limit.		Maximum Stress.				
1	0·130	0·020	0·185	0·011	0·020	13·02	29,100	21·48	48,100	45·00	71·16	Elastic limit for bars 5, 6, 7, and 8 was so doubtful that result not recorded.
2	0·180	0·024	0·250	0·022	0·020	15·84	35,500	27·84	62,350	33·50	60·24	
3	0·254	0·032	0·190	0·025	0·020	17·28	38,300	29·46	66,000	32·50	54·84	
4	0·468	0·072	0·160	0·016	0·025	18·03	40,400	32·46	72,700	28·00	46·26	
5	0·722	0·098	0·217	0·015	0·020	...	...	43·20	96,780	16·50	25·86	
6	0·871	0·080	0·190	0·019	0·019	...	...	50·40	112,900	11·20	15·84	Broke at gauge point; fracture finely crystalline.
7	0·947	0·081	0·181	0·013	0·019	...	...	51·12	114,700	10·00	15·42	
8	1·306	0·050	0·180	0·015	0·017	...	...	44·52	99,760	5·50	5·58	

* See Chap. xix. on the Microstructure of Steel.

Professor Arnold's Results. Annealed Bars.

TABLE LXV.—BARS HEATED TO ABOUT 1,000° C. FOR 72 HOURS AND
ALLOWED TO COOL IN FURNACE FOR 100 HOURS.

Steel No.	Carbon per Cent.	Elastic Limit.		Maximum Stress.		Elongation per Cent.	Reduction of Area per Cent.	Fracture.
		Tons per Square Inch.	Lbs. per Square Inch.	Tons per Square Inch.	Lbs. per Square Inch.			
1	0·08	8·82	19,750	18·34	41,090	52·7	76·7	Grey granular silky edges.
1½	0·21	9·02	20,200	21·25	47,610	42·3	65·7	,, ,, ,, ,,
2	0·38	9·55	21,280	25·02	56,040	35·0	50·6	,, ,, ,, ,,
3	0·59	11·36	25,460	31·87	71,400	22·0	23·3	Crystalline.
4	0·89	16·81	37,650	36·69	82,180	4·5	4·2	,,
5	1·20	16·19	36,280	32·87	73,650	6·0	4·9	,,
6	1·47	10·08	24,200	22·33	50,000	19·0	17·7	Dark grey fibrous.

Author's Results. Soaked Bars.

TABLE LXVI.—HEATED FOR TWELVE HOURS AT 725° C. AND
ALLOWED TO COOL IN MUFFLE.

Treatment.	No.	Total Carbon.	Size Diam. Inch.	Elastic Limit.		Maximum Stress.		Elongation per cent. on 2 Ins.	Reduction of Area per cent.
				Tons per Sq. In.	Lbs. per Sq. In.	Tons per Sq. In.	Lbs. per Sq. In.		
Twelve hours soaking at a temperature of 720° C.	1	0·130	0·454	11·666	26,150	20·000	44,800	42·50	73·21
	2	0·180	0·451	7·625	17,080	27·750	62,170	29·50	61·11
	3	0·254	0·445	15·806	35,400	28·180	63,120	31·00	57·28
	4	0·468	0·450	11·761	26,350	29·308	65,800	30·50	42·70
	5	0·722	0·450	16·163	36,200	38·113	85,380	21·00	35·97
	6	0·871	0·455	15·276	34,200	39·386	88,200	19·50	29·69
	7	0·947	0·448	14·114	31,620	33·734	75,570	23·50	35·44
	8	1·306	0·452	11·687	26,170	33·375	74,750	26·50	34·50

The results of Professor Arnold's compression tests show that the flow of
material decreases gradually, both in the normal and annealed bars, until the
point ·89 per cent. of Carbon is reached, when, in the case of the former,
there is a very slight decrease to 1·5 per cent. of Carbon, and in the case of
the latter the compressibility goes on increasing until, with 1·5 per cent. of
Carbon, it is greater than that of nearly Carbonless steel. In steel which
has been hardened by rapid cooling in water from a high temperature,
according to Arnold's results, ·89 per cent. Carbon again marks the point
of least compression, there being practically no change between this and
1·5 per cent.

Metcalf [*] states that the compressibility of steel goes on decreasing as
the Carbon increases until cast iron is reached, and other metallurgists take
the same view, but how far these are founded upon systematic experiments
with pure Carbon steels without the disturbing influence of other elements it
is difficult to say.

The author is not able to give any results showing the variations in

* *Manual for Steel Users*, p. 46.

hardness of steel due to increasing percentages of Carbon in pure Carbon
steels, but the results obtained by Wahlberg, using Brinell's hardness test
on a set of steels containing somewhat varying percentages of Silicon and
Manganese are given below.[*]

TABLE LXVII.—INFLUENCE OF THE PERCENTAGE OF CARBON ON THE
HARDENING CAPACITY (BRINELL'S RESULTS).

Material No.	Chemical Composition.					Hardness Numbers.		Hardening Capacity.
	C.	Si.	Mn.	S.	P.	Annealed.	Quenched in Water + 20° C.	
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.			
1	0·10	0·007	0·10	0·020	0·026	97	149	1·54
2	0·20	0·018	0·41	0·015	0·027	115	196	1·70
3	0·25	0·30	0·41	0·012	0·028	143	311	2·18
4	0·35	0·26	0·49	0·015	0·027	156	402	2·58
5	0·45	0·27	0·45	0·018	0·028	194	555	2·86
6	0·65	0·27	0·49	0·011	0·028	235	652	2·77
6a	0·66	0·33	0·18	0·010	0·028	202	578	2·86
8	0·78	0·37	0·20	0·011	0·028	231	652	2·82
9	0·92	0·28	0·25	0·012	0·026	258	627	2·43
12	1·25	0·60	0·20	0·510	0·027	262	627	2·39

The influence of rapid cooling from high temperatures on steels con-
taining over ·2 per cent. of Carbon is very marked, the tensile strength
increases, and a most marked reduction of the ductility is found for every
increment in Carbon, as shown by the decrease in elongation and reduc-
tion of area.

The following results were obtained on heating to 900° C. and quenching
in water :—

TABLE LXVIII.—HEATED TO 900° C. AND QUENCHED IN WATER AT 15° C.

Steel No.	Analyses.	Elastic Limit.		Maximum Stress.		Elongation per cent. on 2 Inches.	Reduction of Area per cent.	Remarks.
	Total Carbon.	Tons per Sq. Inch.	Lbs. per Sq. Inch.	Tons per Sq. Inch.	Lbs. per Sq. Inch.			
1	0·130	24·30	54,500	32·34	72,480	28·20	76·26	It was not pos-
2	0·180	...	...	49·92	111,850	6·50	35·28	sible to get a
3	0·254	...	...	70·32	157,500	3·80	13·44	reliable elas-
4	0·468	...	...	†55·44	124,200	1·00	2·64	tic limit for
5	0·722	...	...	61·98	138,840	1·00	2·56	any bar below
6	0·871	...	...	†26·04	58,320	2·00	2·16	No. 1. General
7	0·947	...	...	†21·60	48,400	nil	nil	analyses given in table lvii.

The mechanical properties vary with the initial temperature of heating
and the rapidity of cooling. They may be regulated or modified by re-
heating or tempering to various temperatures.

Influence on Magnetic Properties.—It is well known that prac-
tically carbonless steel cannot be permanently magnetised, and that as

* *Iron and Steel Inst. Journ.*, No. 1, 1901, p. 267.
† The irregular results obtained with these samples were due largely to their having
warped during the quenching, and the first result of applying the load was to straighten
them, which in the case of Nos. 6 and 7 caused them to break off short.

the Carbon increases so the power of retaining magnetism increases, and that this power of retention is increased by hardening. Arnold, as the result of his experiments, found that the magnetic permeability varied inversely as the Carbon present, and that permanent magnetism in hardened steels was directly proportional to the Carbon present up to ·89 per cent., after which there is no change up to 1·5 per cent. Carbon. On heating the hardened steels for thirty minutes at 300° C. the permanent magnetism was reduced to about one-third in the case of ·2 Carbon steel, and remained practically constant until ·89 per cent. of Carbon was reached. After passing this point there was a further reduction of nearly 50 per cent.

It must be borne in mind that all the above results as to the magnetic and general physical properties of Carbon steels refer only to steels of the highest degree of purity, containing practically nothing but Carbon and a little Manganese, and that these results are largely modified by the presence of very small quantities of Silicon, Sulphur, Phosphorus, or additional Manganese, or by any variation in the heat treatment. Professor H. M. Howe [*] has shown how variable these results are by tabulating a large series of results obtained by different investigators, and how difficult, if not impossible, it is to draw any definite conclusion as to the effect of Carbon on tensile strength and other properties of commercial steels, unless fullest details as to composition and treatment are known, and especially is this so in the case of the low Carbon steels up to 0·3 per cent. of Carbon.

Constitution of Steel.—Before considering the various theories which have been advanced to explain the changes induced in steel by heat treatment, and by sudden cooling or quenching, it will be necessary to describe the remarkable phenomena observed during the heating or cooling of steel, as they bear a most important relation to some of the theories advanced.

On heating up a specimen of steel and then allowing the sample to slowly cool, it is found during the cooling that there are certain points at which, instead of the cooling proceeding normally, heat is evolved. These points are known as the critical points, and, thanks to M. Osmond's researches, aided by the wonderfully accurate pyrometer which we owe to the genius of M. Le Chatelier, we have now a complete record of them for specimens, ranging from the softest electrolytic iron to the hardest steel. On heating up the sample there are, of course, the reverse phenomena to those observed during cooling—that is, at certain points there is an absorption of heat, causing a retardation in the rise of temperature. The points at which these changes take place are designated A, those observed during heating up are designated Ac, whilst those observed during cooling are known as Ar. The points at which the retardations take place during heating up correspond exactly with those obtained on cooling under theoretical conditions of equilibrium, but under ordinary conditions of heating and cooling Ac_3 and Ac_1 are found to be some 20° to 40° higher than Ar_3 and Ar_1, whilst Ac_2 and Ar_2 always occur at approximately the same temperature. It has been shown by Professor Howe that, in order to induce the retardation Ar—or, rather, the change that such retardation implies—the steel must first be heated past the point Ac ; and, reciprocally, the change which occurs at Ac cannot take place unless the steel has first been cooled to a point below Ar. It is found that in pure iron there are two critical points during cooling, Ar_3 and Ar_2, whilst in low Carbon steels there are at least three well-recognised critical

[*] *Metallurgy of Steel*, p. 13, *et seq.*

points, Ar_3, Ar_2, and Ar_1, the last being associated with the presence of Carbon.

In medium steels the points Ar_3 and Ar_2 are combined in a single point, and the Ar_1 point becomes much stronger. In eutectoid steels containing ·89 per cent. Carbon there is only a single point corresponding with Ar_1, and in steels containing more than ·89 per cent. Carbon two points are again observable, one corresponding to Ar_1 and a higher one, Ar_{me}, corresponding to the separation of massive Carbide or Cementite.

The following give the approximate temperatures at which the maximum evolution of heat takes place during the cooling of steels of varying Carbon content through the critical ranges :—

		Ar_{me}	Ar_{3}	Ar_{2}	Ar_{1}
Pure iron,	.		900	762	..
0·12 per cent. C.,	.		850	762	715
0·24 per cent. C.,	.		820	762	715
0·53 per cent. C.,	.		730		715
0·89 per cent. C.,	.			715	
1·31 per cent. C.,	.	883		715	

The point Ar_1 is nil in the case of carbonless iron, but increases in importance as the Carbon in the sample increases, being practically the only point observable in hard steel. It is, therefore, clearly a function of the Carbon present, and it is found that above the point Ar_1 the Carbon is in the state of hardening Carbon, whilst below this point it is in the state of cement Carbon, or Carbon which is combined with iron in the form of the definite Carbide, **Fe_3C.** The true state of the hardening Carbon is not known. It is probably Carbon as Carbide of Iron dissolved in the iron.

In regard to the critical points, it has also been shown by M. Osmond that the slower the heating the lower the temperature at which the transformation takes place, and that the slower the cooling the higher the temperature of the reverse transformation.

Professor H. Le Chatelier summed up the chief characteristics of the points Ac_2 and Ac_3 thus :—The point Ac_2 is now known to be almost identical with the disappearance of magnetism in iron ; it is accompanied by a slight absorption of heat, and its position varies little, being little affected by the rate of heating. The reverse change Ar_2 occurs at nearly the same temperature on cooling. The point Ac_3 is characterised by a sudden change in the law of variations of the electric resistance, which is then ten times greater than at ordinary temperatures, but which practically ceases to increase above this critical temperature. This phenomenon, like that of recalescence, is affected by the rate of cooling or of heating.

The consideration of the above, and other experimental work, has led many of our leading metallurgists to form the conclusion that iron exists in different allotropic forms under different conditions of temperature, mechanical treatment, and purity.

Thus, modern views as to the constitution of steel involve two distinct phases for consideration : that which has for its object the study of the relations of Carbon and other elements to iron, and that concerned with the molecular changes occurring in the iron itself.

The Solution Theory.—The recent study of the molecular changes occurring during the cooling of carburised iron and of metallic alloys gener-