ON THE HEAT-TREATMENT OF SOME HIGH CARBON STEELS.[1]

By William Campbell.

Received July 17, 1906.

TABLE OF CONTENTS.

Introduction.—The study of steel and the changes which it undergoes forms one of our most important lines of research at the present day. Our knowledge of the subject has made great advances during recent times and we now know the reason for many of the profound changes of structure and of constitution which take place with changes of temperature. This advance is due in a great measure to the great improvements in pyrometry, to the wide application of metallography and to the use of certain principles of physical chemistry in explaining our results.

From a constitutional point of view steel naturally falls into three groups:

(1) Unsaturated (Arnold): Hypo-eutectoid (Howe), consisting of ferrite and pearlite in the slowly cooled condition. Carbon content less than 0.9 per cent.

(2) Saturated: eutectoid, consisting of pearlite alone. Carbon about 0.9 per cent.

[1] Work carried out in conjunction with Committee F on the "Heat-Treatment of Steel," American Society for Testing Materials.

(3) Supersaturated: hyper-eutectoid, consisting of cementite and pearlite in the normal condition. Carbon content greater than 0.9 per cent.

Previous Work on the Subject.—Since Osmond's classic paper[1] on the transformations of structure which take place within the range of the critical points of steel, a vast amount of research has been done. In many cases both high, medium and low carbon steels have been studied and the work of Arnold,[2] Sauveur[3] and Stead[4] has thrown much light on the subject. In other cases, the effect of varied heat treatment on the physical properties and microstructure of some particular steel has been worked out. Fay and Badlam[5] worked with a low carbon steel of 0.07 per cent. carbon and 0.32 per cent. manganese. Morse[6] used a medium carbon, 0.34 per cent. with 0.22 per cent. manganese. Campbell[7] studied a rail steel with 0.5 per cent. carbon and 0.98 per cent. manganese, while Sargent[8] took up the subject with a high carbon steel (1 per cent. carbon).

The Sixth Report of the Alloys Research Committee[9] deals with the heat treatment of a series of eight steels (0.13 to 1.3 per cent. carbon) at temperatures from 620° to 1100°, and works out their mechanical properties and microstructure.

The present work was undertaken along similar lines because there seemed an opening for research work on steels high in carbon.

Outline of Present Work. Crucible Steel.—A series of six steels,[10] $^5/_{16}$ inch square, whose analyses are given in Table A were used in the form of 12-inch test pieces. Heats were made in a horizontal cylindrical gas forge. The bars were packed in an inner iron tube 2 inches in diameter which was then placed in the axis of a larger tube $3\frac{1}{2}$ inches in diameter by means of which heating was done by radiation and was very uniform.

[1] Bull. Soc. d' Euc. 1895, 10, 476 (Osmond and Stead: "Microscopic Analysis of Metals," Lippincott).

[2] J. Iron and Steel Inst. 1901, 1, 175, 1905 2, 27.

[3] Trans. A. I. M. E. 1896, p. 863, etc.

[4] J. Iron and Steel Inst. 1898 1, 145, etc.

[5] Tech. Quart. 1900.

[6] Trans. A. I. M. E. 1899, 729.

[7] J. Iron and Steel Inst. 2, 359 (1903).

[8] Trans. A. I. M. E. 1901, 303.

[9] Inst. Mech. Eng. London, 1904.

[10] The gift of the Carpenter Steel Co., to whom our thanks are due.

The furnace was charged cold and the heating was so regulated that the maximum temperature was reached in about one to one and a half hours. As soon as the temperature was steady, say five minutes, the gas and blast were turned off and the furnace allowed to cool slowly. This took three and a half or more hours.

An exact record of heating and cooling was kept by means of a LeChatelier pyrometer, the hot junction being in the center of the bundle of steels.

Nine heats were made between 650° and 1200°. The temperatures and heat numbers are given in Table B. These temperatures are very close to those aimed at, *viz.*, 650°, 710°, 750°, 800°, 850°, 900°, 1050° and 1200°.

The critical points of each steel had been previously taken and on heating Ac_1 lay between 730° and 740° while on cooling Ar_1 was found to be 710° to 700°. Ac_{2-3} and Ar_{2-3} were not detected, however. The above temperatures were therefore chosen so that one heat was below the critical points, one was at Ar_1, a third just above Ac_1 *i. e.*, to the region where the change from pearlite into the solid solution is complete. The heats to temperatures above this pass through the region of the change Ac_{2-3} or the solution of cementite (iron carbide) in the solid solution, 1200° producing great overheating.

TABLE A.—ANALYSIS OF STEELS.

No.	C.	Mn.	P.	Si.	S.
1	2.04	0.28	0.014	.....	0.014
2	1.94	0.20	0.009	0.17	0.013
3	1.72	0.075	0.013	0.20	0.018
4	1.61	0.19	0.013	0.19	0.013
5	1.04	0.12	0.012	......	0.017
6	0.70	0.068	0.012	0.141	0.019

TABLE B.—HEAT TREATMENT.

Heat No.	Heated to °C.
3	650
1	715
6	760
2	800
4	855
0	905
5	950
2	1070
8	1200
—	——
A	As rolled.
X	

All of the heats reached their maximum in one to one and one-half hours with the exception of Z to 1070° which took two hours and twenty minutes to heat up. This was due to trouble with the blast.

The mechanical tests were made on a Riehlé testing machine,[1] the elastic limit being determined by drop of the beam and elongation measured in 2 inches.

The figures thus obtained have been tabulated in Tables I to IV and from these tables have been plotted curves I to IV. Instead of following the usual custom and plotting the figures for each steel on a separate sheet, it was found that by making four tables and four curves to correspond, for (1) maximum loads, (2) elastic limits, (3) reductions of area, (4) elongations, a great deal more could be learned of the changes as a whole.

Summary of Results of Mechanical Tests.—From an examination of the mechanical properties, microstructure and fractures, it was immediately seen that the steels fell naturally into two groups, *i. e.*, those consisting of pearlite with an excess of cementite or Nos. 1 to 4 and those consisting of pearlite alone (or nearly so), Nos. 5 and 6. It will be noticed how markedly the curves follow the same general directions and tend to coincide with each other.

Maximum Load. Table I, Curve I.—Of the first four steels, No. 4 with 1.61 per cent. carbon is the strongest with 160,000 pounds per sq. in. The weakest is No. 1 with 144,000 pounds per sq. in. Heating to 650°, which is far below the critical point, causes a reduction of some 30,000 pounds, while heating to a temperature just above the critical point Ac_1 (760°) brings down the maximum load to approximately the same point for each steel, *viz.*, between 95,000 and 100,000 pounds per sq. in. Heating to higher temperatures has but little further effect until we reach heat 8, 1200°, where the maximum load has dropped sharply some 25,000 to 40,000 pounds and now lies between 70,000 and 58,000 pounds per sq. in. In this heat. as in the case of the bars as rolled, No. 1 is the weakest and No. 4 strongest.

Of the last two steels as rolled, No. 5 with 1.04 per cent. carbon has maximum load of 140,000 pounds and No. 6 with 0.70 per cent. carbon has maximum load of 117,000 pounds per sq. in.

[1] Thanks are due to Professor Woolson, Columbia University, for use of this machine.

TABLE I.—MAXIMUM LOADS IN THOUSAND POUNDS PER SQUARE INCH.

Steel. No.	Carbon. Per cent.	As rolled. A.	X.	Heat number and maximum temperature in ° C. 650°. 3.	715°. 1.	760°. 6.	800°. 2.	855°. 4.	905°. 0.	950°. 5.	1070°. Z.	1200°. 8.
1	2.04	144.6	144.0	115.4	114.5	98.8	95.6	93.8	95.2	95.2	99.0	57.4
2	1.94	146.5	146.3	115.2	104.1	95.0	92.0	89.2	95.3	91.8	97.0	61.3
3	1.72	152.8	154.0	126.0	114.1	100.3	98.0	94.0	94.3	95.0	92.3	65.3
4	1.61	162.2	153.2	128.1	117.0	98.6	97.7	95.0	97.3	96.3	94.4	69.8
5	1.04	140.6	141.6	105.4	97.8	86.8	96.6	111.8	115.9	111.5	106.1	112.6
6	0.70	117.4	116.6	95.2	88.7	85.6	94.3	91.3	90.3	90.5	89.5	90.0

TABLE II.—ELASTIC LIMIT IN THOUSAND POUNDS PER SQUARE INCH.

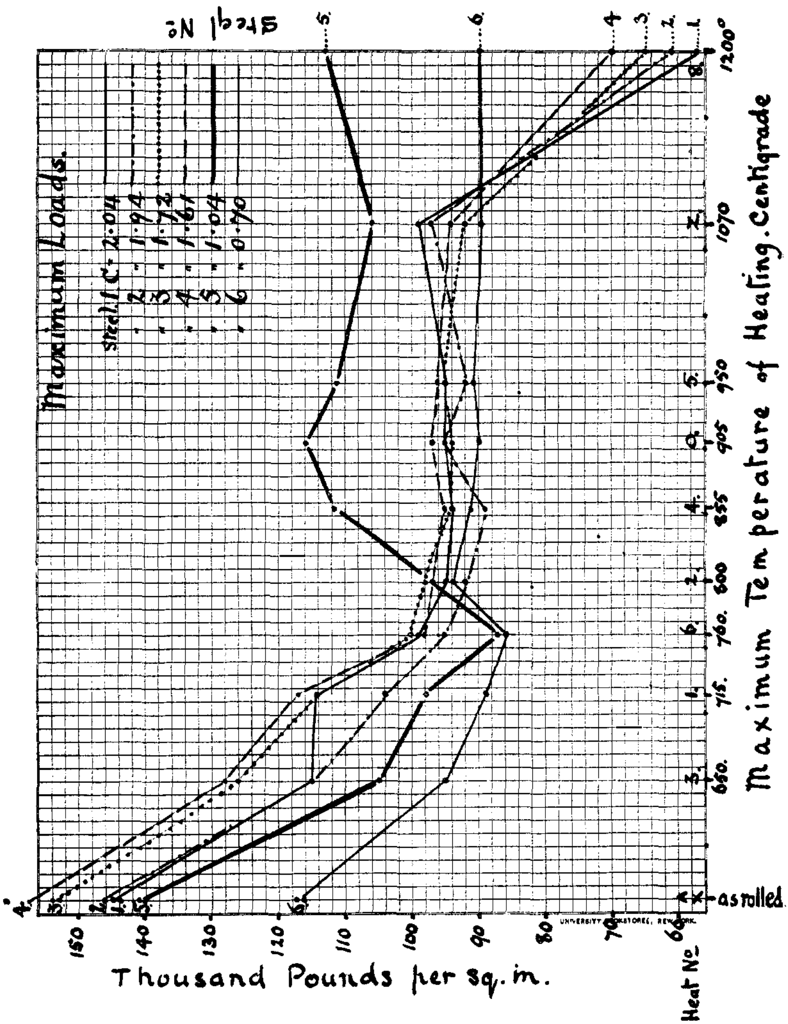
Steel. No.	Carbon. Per cent.	As rolled. A.	X.	Heat number and maximum temperature in °C. 650°. 3.	715°. 1.	760°. 6.	800°. 2.	855°. 4.	905°. 0.	950°. 5.	1070°. Z.	1200°. 8.
1	2.04	101.8	104.2	84.6	83.9	57.7	57.8	55.5	55.3	49.3	49.6	56.0
2	1.94	91.0	91.5	72.6	68.6	50.5	51.0	49.4	49.8	41.7	47.0	....
3	1.72	98.7	97.5	78.3	75.7	50.5	48.7	47.9	48.6	45.2	43.1	50.6
4	1.61	105.2	105.2	85.3	81.3	52.3	53.3	51.3	51.3	48.5	51.4	....
5	1.04	75.8	75.8	57.7	55.2	44.8	46.6	47.2	50.6	46.8	56.5	89.6
6	0.70	65.3	64.2	53.2	49.7	40.2	42.1	42.1	41.4	39.7	57.3	58.5

Table III.—Reduction of Area Per Cent.

Steel. No.	Carbon. Per cent.	As rolled. A.	X.	Heat number and maximum temperature in °C. 650°. 3.	715°. 1.	760°. 6.	800°. 2.	855°. 4.	905°. 0.	950°. 5.	1070°. Z.	1200°. 8.
1............	2.04	3.5	3.0	6.5	6.6	16.2	19.6	13.2	12.6	5.8	2.7	0.4
2............	1.94	6.5	6.0	8.9	12.0	18.8	15.0	12.1	9.5	12.0	7.6	1.4
3............	1.72	5.2	8.7	7.3	18.8	20.5	10.3	12.0	9.6	6.3	4.3	1.0
4............	1.61	8.2	9.1	8.3	21.5	34.0	19.1	14.2	9.4	6.8	2.6	1.9
5............	1.04	22.7	21.8	36.2	41.5	36.6	21.0	11.3	8.8	10.9	10.6	10.7
6............	0.70	27.3	27.0	33.9	45.2	38.7	20.9	20.7	21.8	20.5	17.9	16.8

Table IV.—Elongation in Two Inches.

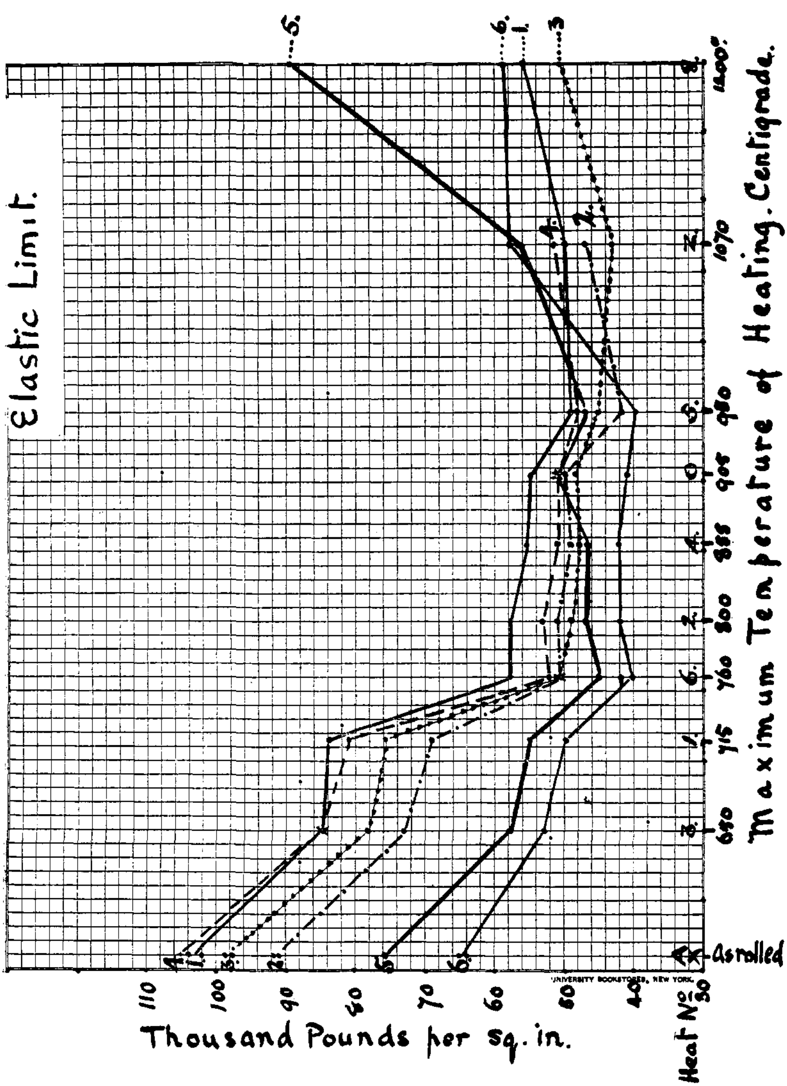
Steel. No.	Carbon. Per cent.	As rolled. A.	X.	Heat number and maximum temperature in °C. 650°. 3.	715°. 1.	760°. 6.	800°. 2.	855°. 4.	905°. 0.	950°. 5.	1070°. Z.	1200°. 8.
1............	2.04	4.5	4.0	6.0	7.0	11.5	12.5	12.0	11.5	6.0	4.5	1.0
2............	1.94	6.0	6.5	8.0	9.5	15.0	17.0	12.5	7.0	9.5	8.5	2.0
3............	1.72	6.5	8.0	8.0	11.5	16.5	10.0	13.5	11.0	7.5	6.0	2.0
4............	1.61	7.0	6.0	..	14.5	20.0	18.5	15.0	11.5	7.5	3.5	3.0
5............	1.04	13.5	12.0	18.0	22.0	26.5	19.0	13.0	13.0	10.5	11.0	11.5
6............	0.70	17.0	17.0	23.0	27.5	27.0	19.0	18.5	18.0	16.5	18.0	16.0



Curve I.

Heating to 650° and 715° brings down the strength regularly as before, while the 760° heat (just above Ac_1) gives the same maximum load of 86,000 pounds per sq. in. for both. In the case of steel No. 5, heating to higher temperatures causes a great rise in strength with a maximum of 116,000 pounds for heat No. 0 (905°). For steel No. 6 the improvement is slight but permanent.

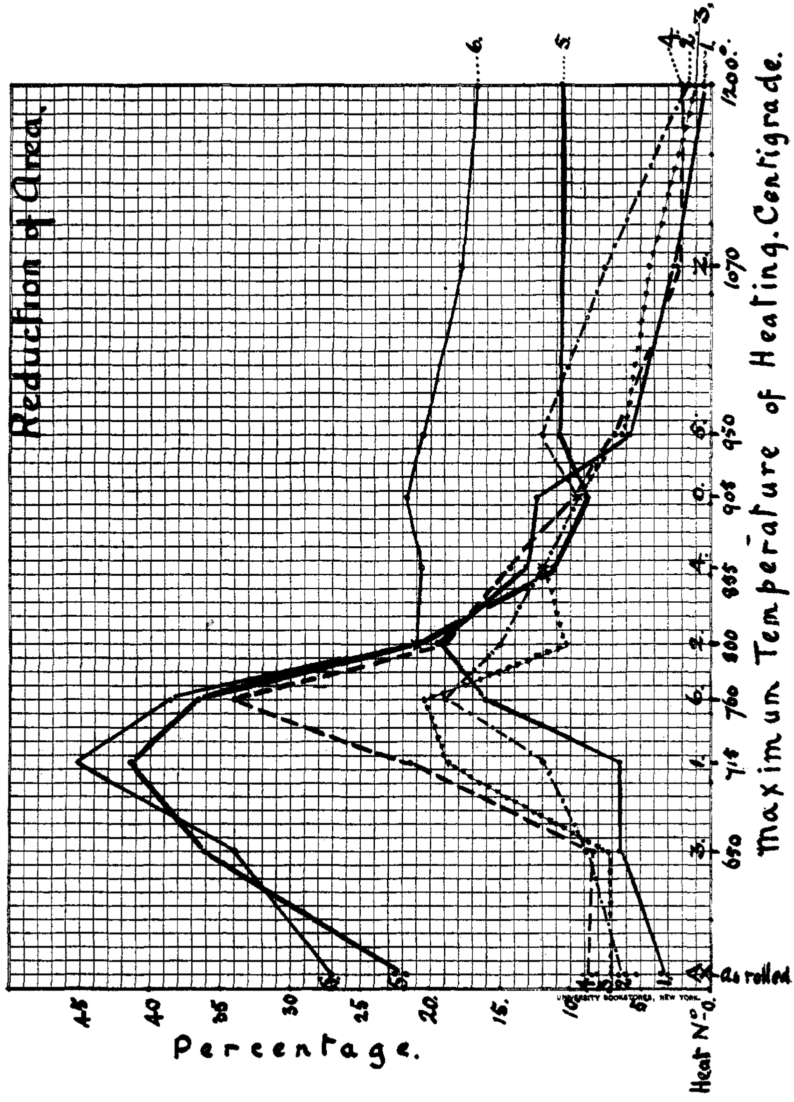
Elastic Limit. Table II, Curve II.—For the first four steels the curves have the same general form as for the maximum loads.



Curve II.

In all, heating to 650° brings about a fall of some 20,000 pounds; heating to 715° gives a slight but regular decrease, while the bars heated to just above the critical point (heat 760°) had an elastic limit down to 50,000–58,000 pounds per sq. in. for steels 1 to 4. For steels 5 and 6 this occurs at 44,800 and 40,200 pounds per sq. in. In the 950° heat, the elastic limit for all of the steels occurs between 40,000 and 50,000 pounds per sq. in.

As in the maximum loads so here heating to higher temperatures (1070° and 1200°) causes an improvement both for steel 5 and steel 6.



Curve III.

Reduction of Area. Table III, Curve III.—In general we find that the ductility increases as the strength falls off. For steels 1 to 4 the reduction of area increases till a maximum is reached for the heat just above the critical point, 760° (in case of steel 1 800°). In the case of steel 4, C = 1.61 per cent., the rise is from 8.2 to 34 per cent., showing some marked change in the structure of the steel.

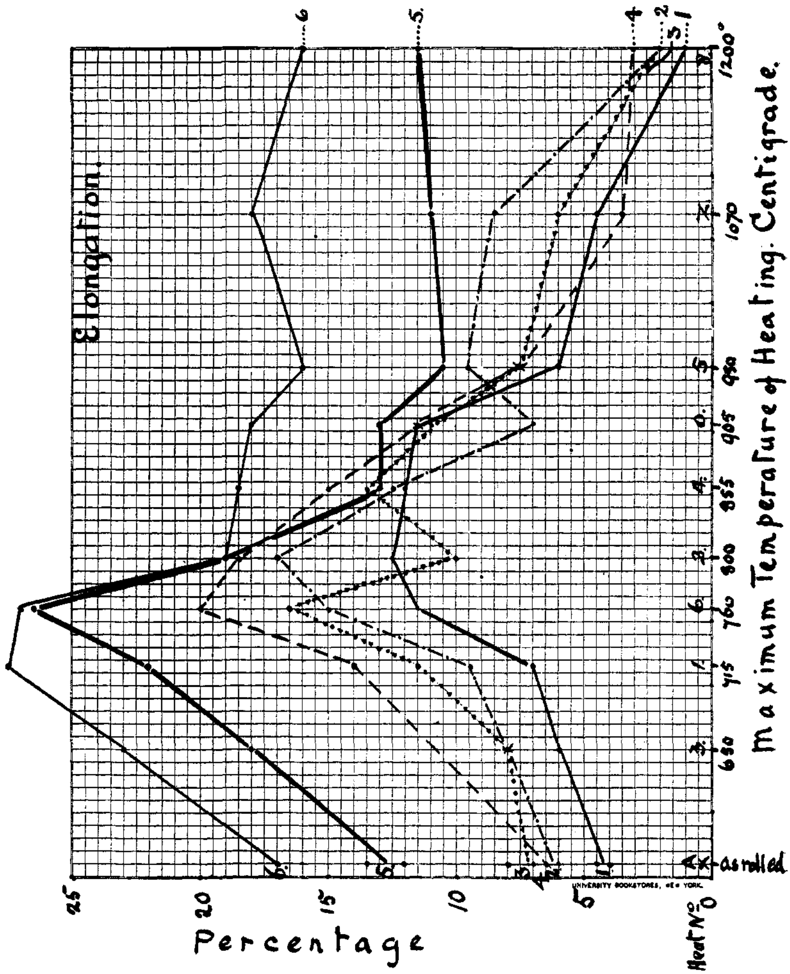
For steels 5 and 6 the maximum occurs in heat 1 to 715°, being almost double that of the bars as rolled. The 760° heat shows a slight fall, but the next heat (800°) shows a fall to 21 per cent., or less than half the maximum. Beyond this point No. 6 shows but little further change, being overheated. No. 5 falls away to about 11 per cent. with the next heat (855°) and then remains constant. It is likewise overheated.

For steels 1 to 4 the 855° heat has produced a fall to between 12 and 14 per cent., while further heating produces a uniform decline to less than 2 per cent. for the 1200° heat. At this point as in the bars as rolled the figures, with one exception, run in the order of carbon content. The irregularity of steel 3 heat 2 to 800° in this and the elongation is due to fracture occurring in the grips.

Elongation in 2 Inches. Table IV, Curve IV.—Heating up to a certain point increases the elongation as well as the reduction of area. The maximum for steels 1 and 2 is found in the 800° heat, for steels 3, 4 and 5 in the 760° heat, while for steel 6, the 715° heat gave a slightly higher figure. As in the case of the reduction of area so here we find that heating to higher temperatures causes a falling off. Steel 6 at 800° and steel 5 at 855° are badly damaged, and further heating has but little further effect. Steels 1 to 4 show a regular falling off until with the 1200° heat the elongation lies between 1 and 3 per cent. (steel 2, heat 0 to 905° is irregular, due to breaking in the grips). As we should expect, there is a very close resemblance between the curves for elongation and those for reduction of area.

Before attempting to explain the above changes which occur in the physical properties around the critical point Ac_1 and elsewhere, it seems best to examine both the fractures and microstructure, when it will be seen that here again we have profound changes taking place at the same points.

Fractures of Test-pieces.—In Fig. 1 we have the whole of the fractures assembled in pairs in such a way that each horizontal



Curve IV.

row (of pairs) corresponds to one steel varying in heat treatment from right to left; each vertical row on the other hand represents one heat and contains 6 different steels. In Figs. 2 to 13 typical fractures are shown, magnified 6 diameters.

Steel 1, C=2.04 per cent.—In Fig. 1 there are two changes noted in steel No. 1. The finest fracture is from heat 2 at 800°. Up to this point there is but little change and Fig. 6 may be taken as the type. From heat 2 onwards to heat 5 at 950° there is a progressive coarsening of the grain and the appearance of a thin crystalline border (Fig. 2). Heat Z shows a great change, for the fracture is very coarse and shows up black, with a strong columnar border. This is even more marked in heat 8, 1200°, where the border is one-third of the radius. Figs. 5 and 9 serve as types.

Steel 2, $C=1.94$ per cent.—The finest fracture occurs in heat 6, 760°, beyond which the grain gets coarser. At heat 5, 950°, in addition to the bright crystalline border there is a marked zone just beneath the surface which is black from graphite. The change can be seen by comparing Figs. 2 and 3. Heating to 1070°, heat Z, completes this precipitation of graphite and the fracture is coarse throughout as in Fig. 4. Fig. 5 shows the fracture of the 1200° heat which is still more coarse, with the strong columnar border as before.

Steel 3, $C=1.72$ per cent.—Fractures of heats 1 and 6 are very fine. Fig. 6 shows the fracture as rolled and may be taken as the type of these first three steels. Fig. 7 shows that of the 715° heat and is also a type. With increase in temperature above the critical point the fractures grow coarser and the crystalline border shows more and more. Heat Z again shows the marked change to a very coarse fracture throughout, with a strong columnar border, as is shown in Fig. 8. Fig. 9 shows the fracture for the 1200° heat, just as coarse but of lighter color; no graphite.

Steel 4, $C=1.61$ per cent.—The smallest fracture is that of heat 6, 760°, which is also the finest. Above this point we get a gradual coarsening of the grain with the great change at 1070°, due to marked overheating, as in steel No. 3. There is but little graphite in Z, however. The 1200° heat shows the change in color, no graphite present.

Viewed as a whole steels 1 to 4 show the finest fracture just above the critical point. From this point onwards the grain grows coarser and a thin crystalline border shows, which as we shall see later is most probably due to decarburization. At heat Z, 1070°, all the fractures become coarse throughout, with a strong columnar border and black color due to graphite. Heat 8, 1200°, gives an even coarser fracture and the border is at least one-third radius deep. Steels Nos. 3 and 4 also show a change in color at this heat, due to the absence of graphite.

Steel 5, $C=1.04$ per cent.—The assembled fractures for this steel (Fig. 1) show a marked change. As rolled the fracture shows a dark core as seen in Fig. 10. Heating to 650° yields a smaller fracture shown in Fig. 11. Heat 1 to 715° gives the finest fracture, and this is shown in Fig. 5. The 760° heat also yields a fine fracture but in heat 2, 800°, there is considerable coarsening. Heating to 855° causes a marked change and produces a coarse fracture throughout, showing that overheating occurs here. From this point on the fractures are all coarse and Fig. 13, heat Z to 1070°, may be taken as a type.

Steel 6, C = 0.70 per cent.—The assembled fractures are very similar to those of the last steel, the 715° heat yielding the finest fracture. Overheating, however, is seen to occur at 800°. The dark center of the bar as rolled (as in Fig. 10) continues to heat 6 at 760°. This is apparently due to the outer part of the bar rupturing across the grain while the core breaks like fibre. Thus in steels 5 and 6 overheating occurs at such low temperatures as 855° and 800°. The finest fracture is given by the 715° heat. However, it may be remarked that the finest fracture does not necessarily mean the finest grain in the steel. Reduction of area has taken place and so in steels having grains of equal size, the one with the greater reduction of area would apparently have the finer grain as judged by fracture. When the microstructure is taken into account it is seen that the grain from the 760° heat is as fine as, if not finer than, any other.

Examination of Microstructure.—Sections were cut from each bar, ground down on an emery wheel, rubbed on emery papers and finally polished with broadcloth and rouge, as has been described in detail elsewhere.[1]

It was found that either a 2 per cent. solution of nitric acid in alcohol or a 5 per cent. picric acid in alcohol developed the structure in a very satisfactory manner.

To observe the general changes which take place a power of 44–88 diameters is used in an ordinary microscope in conjunction with a Sorby-Beck illuminator.[1] Then for more detailed work a higher magnification of 260–500 diameters was obtained by using a LeChatelier stand. Over 100 photographs were taken to record the various changes which take place. By choosing types, however, these have been represented by Figs. 14 to 25.

Structure of the Original Steels as Rolled.—Steel 1 consisted of

[1] Stead: Cleveland Inst. Engineers, February 26, 1900; Campbell: School of Mines Quart. 25, 390.

both patches and veins of cementite in a groundmass of pearlite, much of which is in the sorbitic condition. In a longitudinal section the patches of cementite are drawn out, while at the edge of the specimen the pearlite grain with its cementite envelope is elongated in the direction of rolling. Hence we may judge that rolling was finished after the cementite had begun to separate out, *i. e.*, in region of Ar_{2-3}. The comparatively rapid cooling of bars of $^5/_{16}$ inch cross-section would produce pearlite in the sorbitic or unsegregated condition.

Steel 2 is similar but contains fewer patches of cementite.

Steel 3 consists of medium-sized grains of pearlite surrounded by irregular envelopes of cementite, and practically no patches as occur in Nos. 1 and 2. The pearlite varies from well-laminated to sorbitic.

Steel 4 shown in Fig. 14 $\times 260$ has a structure similar to steel 3.

Steel 5 as rolled consists of pearlite alone in medium-sized grains, whose texture varies from very fine to coarse.

Steel 6 shows some ferrite at the surface. The rest of the section consists of medium-sized grains of pearlite with very thin films of ferrite which disappear towards the center. Much of the pearlite is sorbitic.

As in the case of the physical properties and fractures the steels naturally fall into two groups, (1) steels 1 to 4 and (2) steels 5 and 6, according to their carbon content.

Changes of Structure in Steels 1 to 4.—Such heat treatment as the steels have undergone produces more or less decarburization. This first shows in heat 6, 760°, becomes more visible in the heat to 800° and probably gives the crystalline border to the fracture, while at 1200° it has penetrated deep into the steel. This is shown in Fig. 17 $\times 44$, which is taken from the corner of steel 1 heat Z, 1070°. On the left-hand side we see the normal structure, globular cementite in pearlite, while the center of the photograph consists of pearlite alone, 0.9 per cent. carbon. At the extreme right ferrite makes its appearance at the corner of the specimen and the carbon content falls below 0.4 per cent. The same change through decarburization occurs in steels 5 and 6.

Change in the Pearlite.—In the bars as rolled the pearlite is either very finely laminated or in the sorbitic condition. Heating to even 650° causes a change and the pearlite tends to become granular, the cementite drawing up into globules which polish in relief. The higher the temperature up to the critical point the stronger the segregation of the cementite of the pearlite. The size of grain of the pearlite, however, does not show any apparent change, until the critical point Ac_1 is passed, when the steel is refined as regards the pearlite. Heating to temperatures above this point produces larger and larger grains of coarser and coarser pearlite. The coarseness depends on the rate of passing through Ar_1 which was comparatively slow in these experiments. The size of grain as rolled is given in Fig. 14 $\times$ 260. That of steel No. 3 heated to 1200° is given in Fig. 23 $\times$ 44 diameters only, and is over ten times as great.

Change in the Cementite.—As rolled the cementite occurs as veins or patches more or less drawn out in the direction of rolling. Heating to 650° or above causes these veins to break down, due to the tendency for the cementite to take a globular form. The higher the temperature the greater the segregation. Fig. 15 $\times$ 260 shows steel No. 3, heat 2 to 800°, while Fig. 16 shows steel No. 2, heat 5 to 950°, in which globules of cementite have become very coarse indeed. Figs. 14, 15 and 16 illustrate the complete change very well indeed; but as the temperature rises above the critical point Ac_1 (therefore in all heats above 760°) the cementite also tends to dissolve in the solid solution formed by the transformation of the pearlite (and called austenite, martensite, hardenite, etc.). On cooling down again all of this dissolved cementite separates out, as a rule on the undissolved grains of cementite but lacking these, around the grain of the solid solution as an envelope. Arnold,[1] on the other hand, maintains that cementite only dissolves in the solid solution (hardenite) when the temperature has become a little above 900° and on cooling falls out of solution completely at about 900°. He also "advances the proposition that the Fe_3C of cementite and the Fe_3C of pearlite are physically different substances though identical in chemical composition."

As the temperature rises a point is reached where any cementite which remains undissolved breaks down into ferrite and graphite. As a rule we find a kernel of graphite with a skin of ferrite, but this latter may dissolve in the solid solution. Fig. 18 $\times$ 260 shows the center of steel No. 1, heat 8 to 1200°, while Fig. 20 shows steel No. 2, same heat, from near the side. These sections show only ferrite

[1] Arnold: J. Iron and Steel Inst. 1899, 1, p. 85; 1905, 2, 27.

and graphite in a groundmass of pearlite and little or no cementite has been dissolved. Outside this graphite zone, however, the cementite has all dissolved and on cooling has separated as seen in Figs. 19 and 21. Fig. 19×260 shows outer zone of steel No. 2, heat 8 to 1200°, and Fig. 21×44 shows outer zone of steel No. 1, same heat, in which all of the cementite has separated out as veins and as sheets within the very coarse grain of the pearlite. This zone lies between the central core and the outside decarburized covering, and seems to show the beginning of the next change.

In the case of steels 3 and 4 the change of cementite into ferrite-graphite kernels occurs at 1070° or lower. When these steels are heated up to 1200° the whole of the cementite is taken into solution and separates out again on cooling as is shown in Figs. 23, 24 and 25. Fig. 23×44 diameters shows steel 3 heated to 1200° and slowly cooled, consisting of very coarse grains of pearlite surrounded by irregular envelopes of cementite, some of which has separated out within the grain as is characteristic of overheated material. (Fig. 24×44 oblique illumination shows up the change in color by changing the light from vertical to oblique, and now the pearlite appears light and the cementite dark.) Fig. 25×44 shows steel No. 4 heated to 1200° which is similar to the last but has a much smaller grain. The wavy irregular appearance of the cementite is well shown in Fig. 22×260 steel No. 3 heated to 1200°. The photo is taken from near the edge of the specimen.

To sum up, we find two changes taking place. The first occurs at a constant temperature, the change Ac_1 the transformation of the pearlite. The second is the change in the cementite. Heating causes the cementite to segregate, the higher the temperature the greater the segregation. At a certain temperature which differs in the different steels this segregated cementite breaks down into ferrite and graphite.[1] In steel No. 1 this occurs at 1200°, began at 950°, was marked at 1070° and complete at 1200° in steel No. 2. In steel No. 3 it was complete at 1070° while in steel No. 4, though not showing at 950°, the 1070° heat shows it together with the next change. Lastly, we have the complete solution of the cementite, the temperature of which also varies. In steels Nos. 1 and 2 this occurs above 1200°, in steels Nos. 3 and 4 it occurs at

[1] According to Arnold and McWilliam (J. I. S. I. 1905, 2, p. 47), this change takes place on cooling and occurs at a low red heat.

1200°, though steel No. 4 shows it beginning at 1070°. This dissolved cementite separates out on cooling as an irregular envelope to the pearlite grains.

These changes are of the utmost importance in the making of malleable castings, as well as in the manufacture of cutlery, etc. It must be added here that in different parts of bars of steels Nos. 1 and 2 as rolled traces of graphite were found in the center, and evidently formed during the rolling. These persist and are found in the 1070° heat, but for the sake of clearness they have not been considered here.

Change of Structure in Steels 5 and 6.—The changes which take place in the pearlite by heating up to the critical point are the same as described above.

Steel 5, C = 1.04.—Heating to 800° causes a growth in the pearlite grain and allows the cementite in excess of the eutectoid ratio (0.9 per cent. carbon) to separate out as a thin film round the pearlite grain. Heating to 855° so coarsens the pearlite that the steel is overheated. The cementite film has disappeared.

Steel 6, C = 0.70 per cent.—Heating up to the critical point in places produces a marked segregation of the cementite of the pearlite resulting in coarse lamination. Heating to 800° causes a great increase in grain size and the film of ferrite, seen in the section as rolled, has now changed to grains. The steel is overheated at this low temperature.

Effect of Heat Treatment upon the Structure and Its Bearing on the Mechanical Properties.—From the above work it is noted that heating to temperatures up to the critical point Ac_1 in general, increases the ductility at the expense of the strength. The fractures show no marked change in size of grain till the critical point is reached, though of course they decrease in area. Under the microscope this is explained by (1) the breaking down of the veins of cementite and its segregation, tending to take a globular form and (2) a change in the character of the pearlite. The size of grain of the pearlite does not change until the critical point has been passed and it is therefore necessary to heat to a point just above Ac_1 for complete refining.

In the case of the steels high in carbon (1 to 4) the strength, as compared with that of the refined bars, is changed but little on heating to higher temperatures, until at the maximum tem-

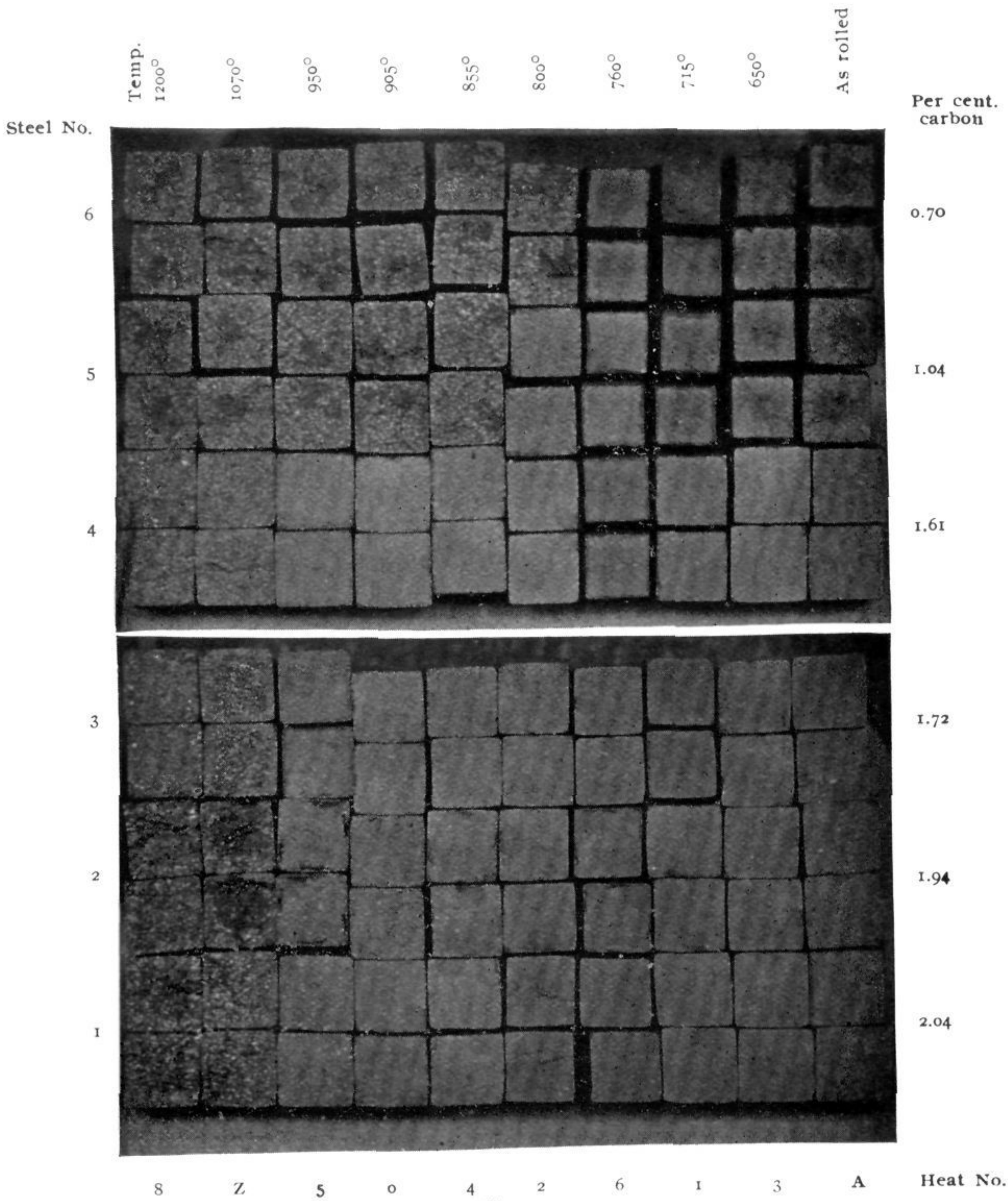

Temp.
1200°
1070°
950°
905°
855°
800°
760°
715°
650°
As rolled
Steel No.
6
5
4
3
2
1
Per cent. carbon
0.70
1.04
1.61
1.72
1.94
2.04
8
Z
5
0
4
2
6
1
3
A
Heat No.

Fig. 1.

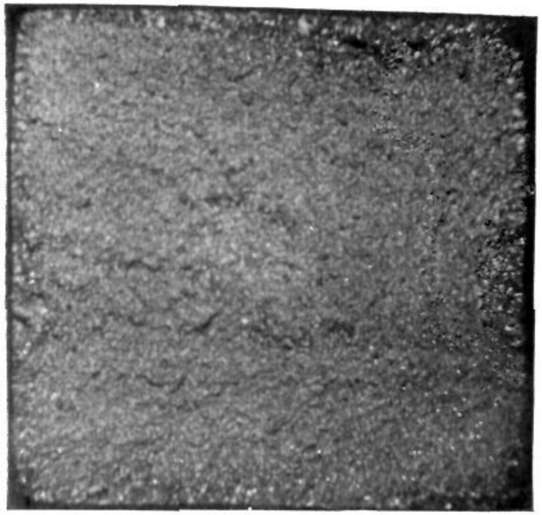


Fig. 2. Steel 2, heat 905°.

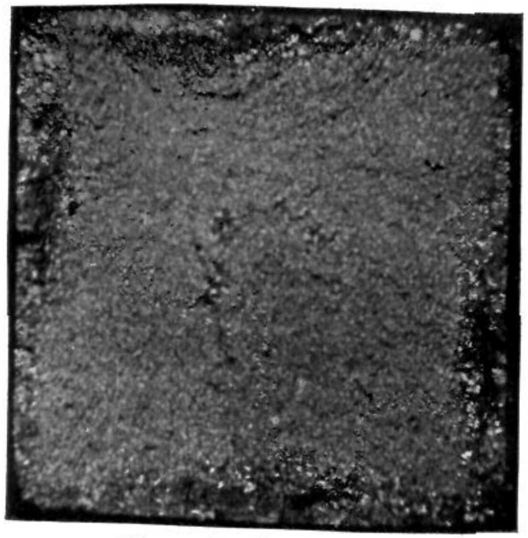


Fig. 3. Steel 2, heat 950°.

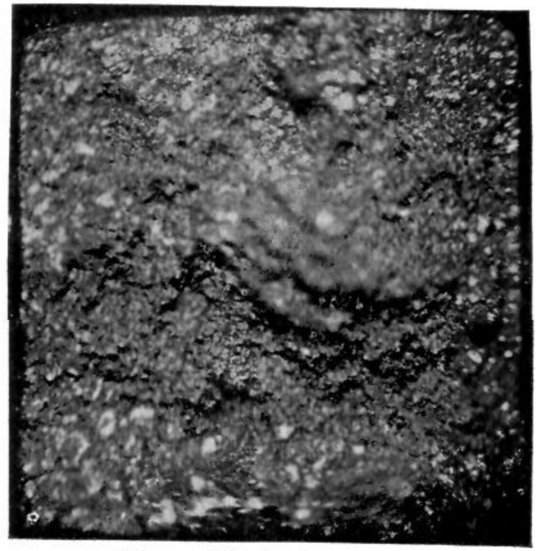


Fig. 4. Steel 2, heat 1070°.

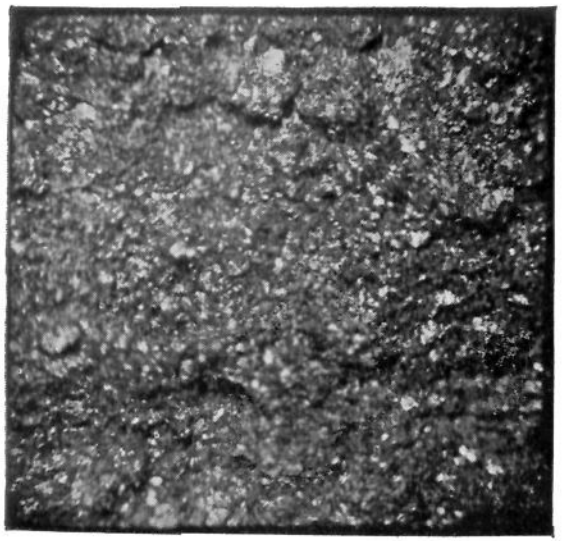


Fig. 5. Steel 2, heat 1200°.

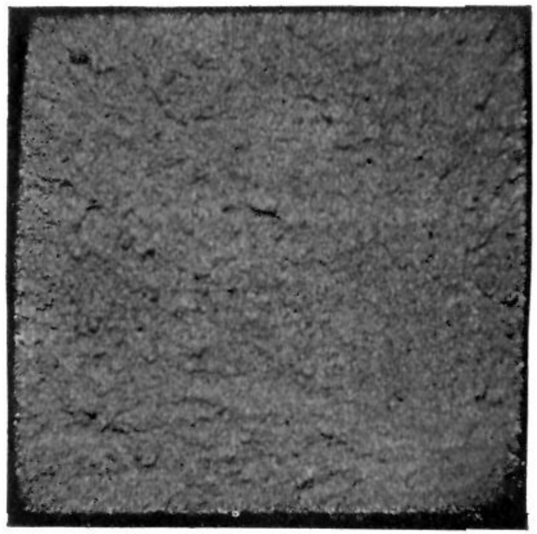


Fig. 6. Steel 3, as rolled.

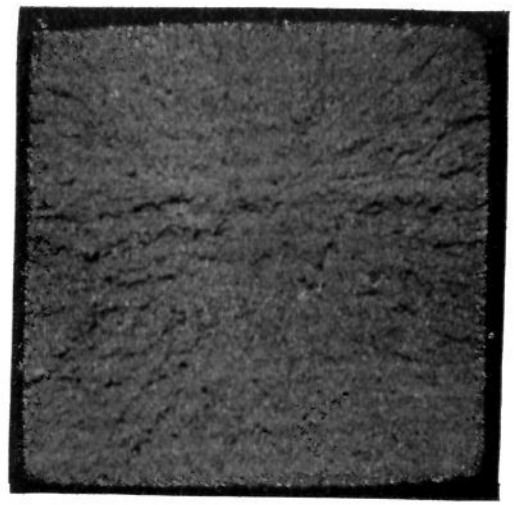


Fig. 7. Steel 3, heat 715°.

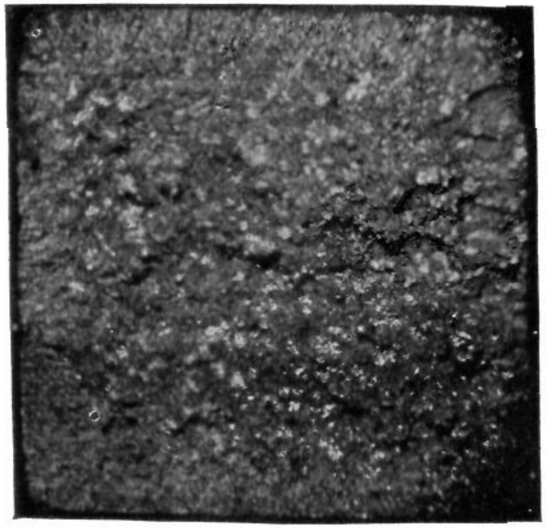


Fig. 8. Steel 3, heat 1070°.

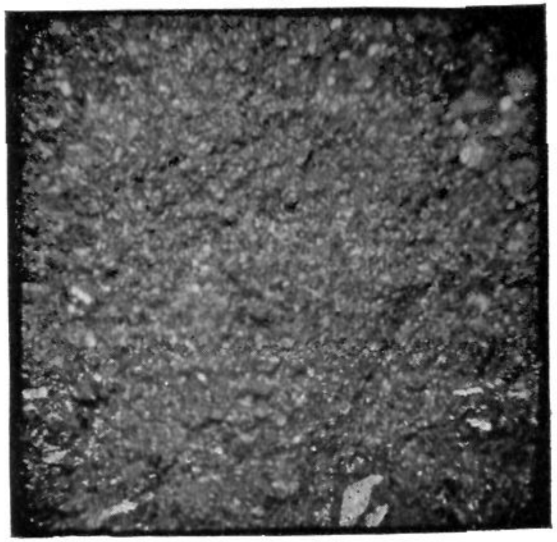


Fig. 9. Steel 3, heat 1200°.

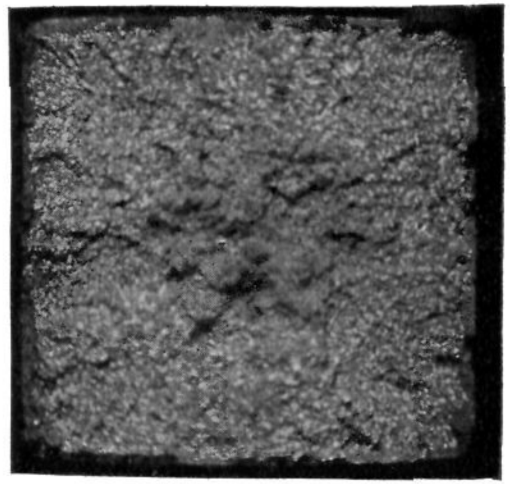


Fig. 10. Steel 5, as rolled.

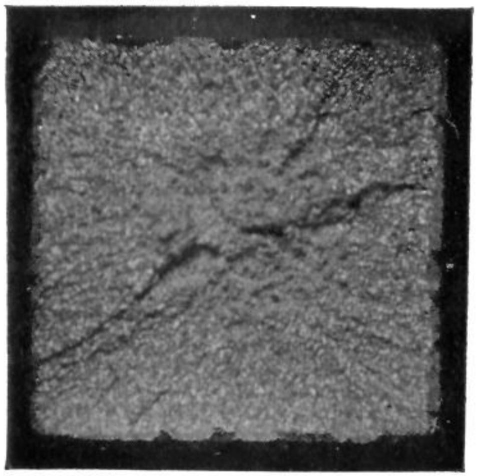


Fig 11. Steel 5, heat 650°.

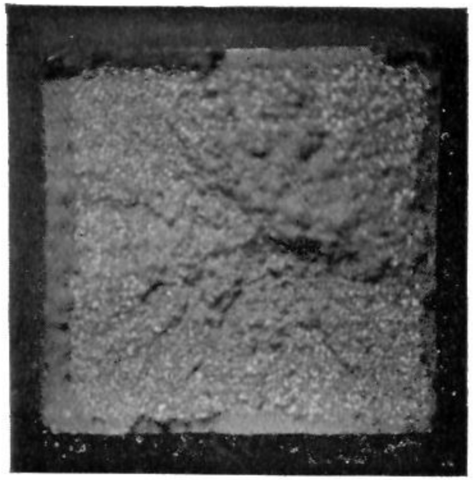


Fig. 12. Steel 5, heat 715°.

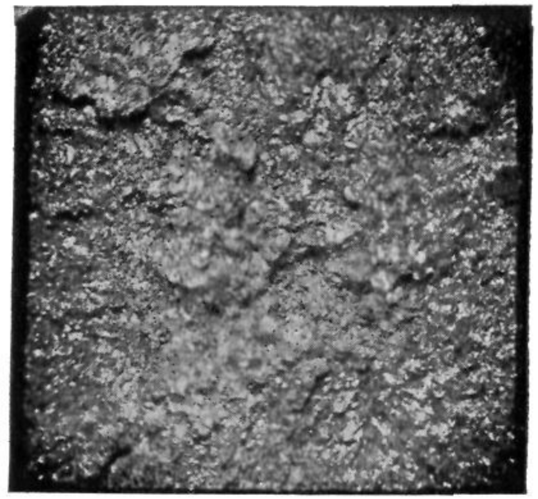


Fig. 13. Steel 5, heat 1070°.

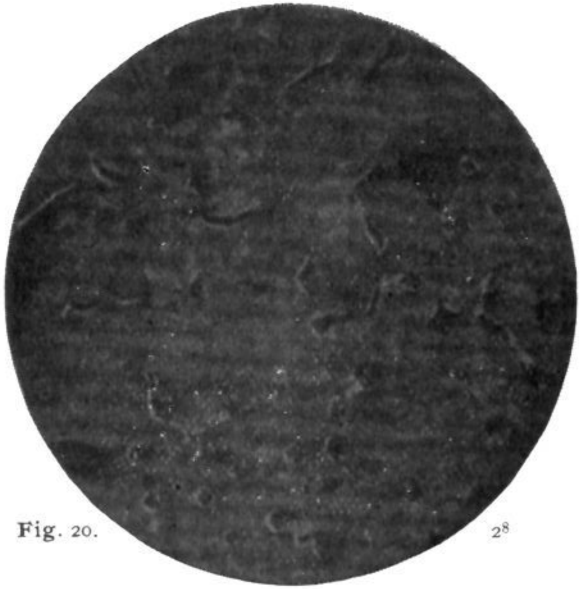


Fig. 20. 2^8

Fig. 21. 1^8

Fig. 22. 3^8

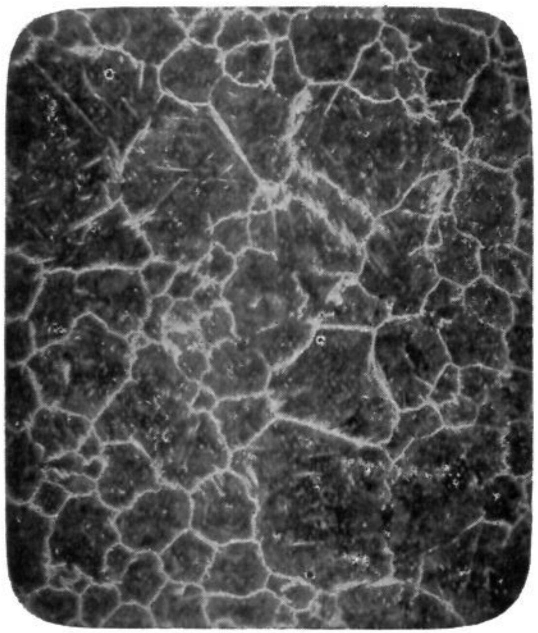


Fig. 23. 3^8

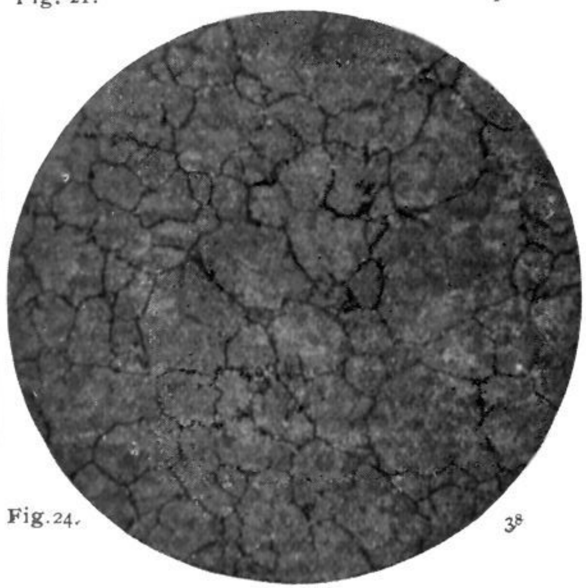


Fig. 24. 3^8

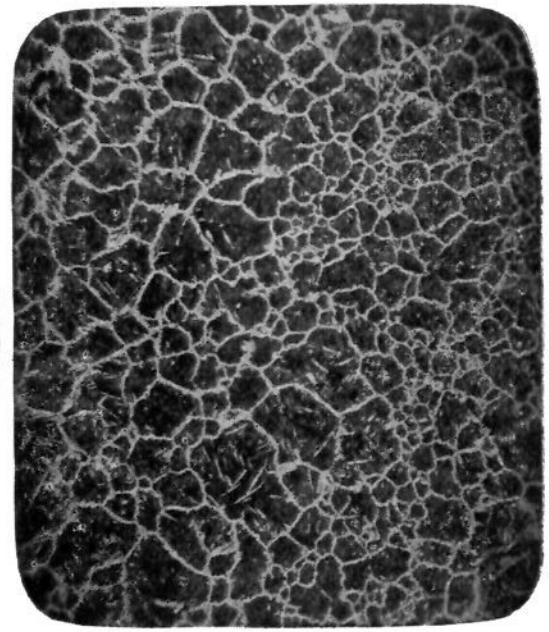


Fig. 25. 4^8

perature, 1200°, the maximum load takes a sudden drop and we have great overheating. The ductility on the other hand shows a steady fall to almost nil. An examination of the fractures shows a steady increase in size of grain up to 1070° at which point they suddenly become exceedingly coarse and show graphite. The microstructure shows a steady increase in the size of grains of the pearlite and of the segregation of the cementite. At the 1070° heat we see the breaking down of the segregated cementite into ferrite and graphite, with a great coarsening of the pearlite. In steels Nos. 3 and 4 the maximum heat, 1200°, produces another change, whereby the whole of the cementite is taken into solution resulting in a coarse network of cementite round large grains of pearlite. Such a structure accounts for the falling off in strength and ductility, while in the case of steels Nos. 1 and 2 this fall is apparently due to extreme coarseness of grain.

In the case of the steels low in carbon heating to temperatures above the critical point increases the strength compared with that of the refined bars. On the other hand, the ductility falls off. The fractures show that a temperature of 855° overheated steel No. 5, while 800° overheated steel No. 6, both of which are comparatively low temperatures. The microstructure shows that the pearlite has become coarse in grain and texture at these points, but it hardly accounts for the marked overheating at so low a temperature.

Thus we see that for each change in microstructure there is a corresponding change in mechanical properties and in fracture. So close are these relations that with little practice the latter can be predicted with certainty from the former.

Conclusion.—The above work is preliminary to a study of another series of six high carbon steels ranging in equal steps from 1 to 2 per cent. carbon and of larger cross-section, whereby it is hoped to work out definitely the change in steel of cementite = ferrite + graphite.

In conclusion I wish to acknowledge my indebtedness to the Carnegie Institution of Washington for a grant to carry on the work. I have also to thank Professor Howe and other friends for encouragement and advice.

LIST OF ILLUSTRATIONS.

Fig. 1.—Assembled fractures of test-pieces.

Figs. 2 to 13.—Fractures $\times$ 6 diameters.

Fig. 2.—Steel	2.	C = 1.94	per cent.	Heat 0.	905° C.
Fig. 3.— "	2.	C = 1.94	"	" 5.	950° C.
Fig. 4.— "	2.	C = 1.94	"	" Z.	1070° C.
Fig. 5.— "	2.	C = 1.94	"	" 8.	1200° C.
Fig. 6.— "	3.	C = 1.72	"	As rolled.	
Fig. 7.— "	3.	C = 1.72	"	Heat 1.	715° C.
Fig. 8.— "	3.	C = 1.72	"	" Z.	1070° C.
Fig. 9.— "	3.	C = 1.72	"	" 8.	1200° C.
Fig. 10.— "	5.	C = 1.04	"	As rolled.	
Fig. 11.— "	5.	C = 1.04	"	Heat 6.	650° C.
Fig. 12.— "	5.	C = 1.04	"	" 1.	715° C.
Fig. 13.— "	5.	C = 1.04	"	" Z.	1070° C.

Fig. 14.—25.—Microstructure.

Fig. 14.— "	4.	C = 1.61	"	As rolled $\times$ 260.	
Fig. 15.— "	3.	C = 1.72	"	Heat 2.	800° C. $\times$ 260.
Fig. 16.— "	2.	C = 1.94	"	" 5.	950° C. $\times$ 260.
Fig. 17.— "	1.	C = 2.04	"	" Z.	1070° C. Corner $\times$ 44.
Fig. 18.— "	1.	C = 2.04	"	" 8.	1200° C. Center $\times$ 260.
Fig. 19.— "	2.	C = 1.94	"	" 8.	1200° C. Between center and outside $\times$ 200.
Fig. 20.— "	2.	C = 1.94	"	" 8.	1200° C. Near center of side $\times$ 60.
Fig. 21.— "	1.	C = 2.04	"	" 8.	1200° C. Between center and outside $\times$ 44.
Fig. 22.— "	3.	C = 1.72	"	" 8.	1200° C. Near outside $\times$ 260.
Fig. 23.— "	3.	C = 1.72	"	" 8.	1200° C. Center $\times$ 44.

Fig. 24.—The same, oblique illumination.

Fig. 25.—Steel 4. C = 1.61 per cent. Heat 8. 1200° C. Near center $\times$ 44.

METALLOGRAPHIC LABORATORY,
DEPT. OF METALLURGY,
COLUMBIA UNIVERSITY.

[CONTRIBUTION FROM THE CHEMICAL LABORATORY OF HARVARD COLLEGE.]

A REVISION OF THE ATOMIC WEIGHT OF BROMINE.

BY GREGORY PAUL BAXTER.

Received July 20, 1906.

IN numerous investigations in this laboratory upon the atomic weights of certain metals, in which metallic bromides were first titrated against the purest silver, and then the precipitated silver bromide was collected and weighed, the relation between the silver used in the titrations and the silver bromide obtained has yielded