

PREPARATION AND PROPERTIES OF PURE IRON ALLOYS:

II. MAGNETIC PROPERTIES OF IRON-CARBON ALLOYS AS AFFECTED BY HEAT TREATMENT AND CARBON CONTENT.

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ABSTRACT.

This paper discusses the results of a study of the effect of heat treatment and chemical composition on the magnetic properties of a series of unusually pure iron-carbon alloys ranging from pure iron to 1.6 per cent carbon. They were given the following heat treatments: (1) Two sets of specimens were hardened by quenching from temperatures above the critical range. They were then drawn back to successively higher temperatures. (2) Another set was annealed in vacuo from suitable temperatures.

Magnetization curves and hysteresis data were taken after each heat treatment and microscopical analyses were made after certain selected heat treatments. The hardened alloys when drawn back to successively higher temperatures showed marked changes in the normal induction, residual induction, and coercive force which correspond to transformations of the material. They also showed variations in the maximum intensity of magnetization as computed from the reluctivity relationship. Microscopic analyses confirmed in the majority of cases the fact that the number of values of intensity indicates the number of constituents present in the material. Variations in the maximum permeability for some alloys show greater differences than other magnetic quantities.

Comparing the magnetic properties with the carbon content there were found certain changes in these properties as the percentage of carbon content was increased. The reluctivity relationship was employed to predict the number of constituents present with different percentages of carbon. More extensive investigation is necessary before general quantitative correlation can be made.

CONTENTS.

	Page.
I. Introduction.....	610
II. Preparation and analysis of alloys.....	610
III. Heat treatment.....	611
1. Hardening.....	611
2. Tempering.....	611
3. Annealing.....	612
IV. Apparatus.....	612
V. Magnetic quantities.....	613
VI. Experimental results.....	615
1. Hardened and tempered specimens.....	615
2. Annealed specimens.....	628
VII. Microscopical analysis.....	630
VIII. Discussion.....	630
IX. Summary.....	633
X. Bibliography.....	635

I. INTRODUCTION.

In a recent paper¹ the magnetic properties of a quenched and subsequently tempered eutectoid carbon steel were discussed. Particular use was made of the reluctivity relationship and its metallurgical significance. It was suggested that this method of analysis might also be applicable to the whole iron-carbon series. Since, through the metallurgical division of the Bureau of Standards, there were available iron-carbon alloys of unusual purity, it seemed desirable to extend the investigations on the eutectoid-carbon steel to alloys having higher and lower percentages of carbon. This seemed especially desirable, since in nearly all previous investigations with varying amounts of carbon (some of which are discussed below) the test specimens contained appreciable amounts of impurities, particularly manganese. This paper gives, therefore, the results of such an investigation. While it is realized that care must be exercised in drawing general conclusions from results obtained with a limited number of specimens, it is felt that the unusual purity of the specimens used in the present investigation warrants the publication of the data and such conclusions as may be drawn directly from the evidence at hand. Further experiments are necessary in order to make generalizations.

II. PREPARATION AND ANALYSIS OF ALLOYS.

The test specimens of iron-carbon alloys used in the experiments herein described were prepared with great care by the metallurgical division of the Bureau of Standards. The pure iron was obtained electrolytically according to methods fully described in a recent paper,² to which the reader is referred for details. Ingots produced by melting the electrodeposited iron with the requisite amount of carbon in a vacuum furnace were rolled hot into plates approximately 9 by 4 by $\frac{1}{2}$ inch. In order to facilitate subsequent machining, it was necessary to anneal some of the plates before cropping off the ends to reduce the length uniformly to 6 inches. Each plate was then cut into three strips, the two outer strips approximately $\frac{5}{8}$ inch wide being retained by the metallurgical division for tensile tests, and the inner strips of variable width given to the magnetic laboratory for investigation of the magnetic properties of these alloys. The inner strips were turned into as many cylindrical rods (7 mm diameter) as was

¹ Nusbaum, Cheney, and Scott, *B. S. Sci. Papers*, No. 404; 1920.

² R. P. Neville and J. R. Cain, *B. S. Sci. Papers*, No. 453.

possible. Table 1 shows the chemical composition of these rods as determined by the chemistry division of the Bureau of Standards.

TABLE 1.—Constituents ¹ of Iron-Carbon Alloys Arranged in Order of Carbon Content.

No.	Constituents in percentages.				No.	Constituents in percentages.			
	C	S	Si	Mn		C	S	Si	Mn
171.....	0.018	0.011	0.004	Trace.	175.....	0.88	0.011	0.018	0.006
161.....	.14	.020	.01	0.002	174.....	.96	.009	.017	.004
160.....	.23	.020	.006	.004	169.....	1.28	.008	.025	Trace.
170.....	.32	.009	.007	Trace.	172.....	1.32	.011	.006	Trace.
198.....	.39	.009	.004	Trace.	168.....	1.55	.003	.004	Trace.
181.....	.52	.011	.003	Trace.	159.....	1.60	.005	.005	Trace.

¹ Contents of other elements so small as to be entirely negligible.

III. HEAT TREATMENT.

1. HARDENING.

The rods (6 inches long and 7 mm in diameter) were selected, as far as possible, to include one rod from each type of alloy used. They were cut into two equal lengths and hardened in the following manner: The rods were heated in an electric resistance furnace wound with nichrome wire. The specimens were in the furnace for approximately one-half hour, the first 15 minutes of this time being consumed in heating the specimens up to the final quenching temperature, the other 15 minutes in maintaining the final temperature constant before quenching by plunging the specimens end on and stirring until cooled in a bath at room temperature consisting of a layer of water approximately 1 foot deep covered with a layer of oil having the same thickness. The temperatures (read by means of a platinum-platinum-rhodium thermocouple) from which the specimens were quenched depended, of course, on the amount of carbon and are shown in column 2, Table 2.

2. TEMPERING.

After the quenching the hardened specimens were accurately ground to a uniform diameter of 6 mm. One rod 3 inches long of each carbon content was selected and reheated to the successively higher temperatures shown in column 5, Table 2. At each reheating the specimens were maintained at the desired temperature for 20 minutes and then allowed to cool slowly in lime. Up to about 200° C. an oil bath was used for heating the specimens, then a bath of sodium nitrate and potassium nitrate, and for the higher temperatures a lead bath. A mercury-in-glass thermome-

ter was employed for reading temperatures of the oil bath, a chromel-alumel (14 B. & S. gage) thermocouple for reading temperatures of the sodium and potassium nitrate bath, and a platinum-platinum-rhodium thermocouple for temperatures of the lead bath. The companion set of hardened specimens was given a treatment similar to the above, but was drawn to alternate temperatures, as shown in column 6, Table 2.

3. ANNEALING.

Another set of rods (unhardened) was selected with one rod from each percentage of carbon content and accurately turned on a lathe to 6 mm diameter. They were then slowly heated in an evacuated electric resistance furnace wound with platinum foil and heated above the critical temperature, as shown in Table 2. The time required to reach this maximum temperature (read by means of a platinum-platinum-rhodium thermocouple) varied from one and one-half hours to three hours. In all cases the maximum temperature was maintained for one-half hour, then the temperature was slowly lowered by reducing the current through the heating coil, averaging about three and one-half hours, until a temperature varying between 100 and 150° C. was reached. The electric circuit was then broken and the specimen allowed to cool to room temperature with the furnace. It was believed that decarburization at the surface of the specimen annealed in this manner was so small as to be inappreciable.

TABLE 2.—Heat Treatment of Iron-Carbon Alloys.

Specimen No.	Quenching temperature.	Specimen No.	Annealing temperature.	Drawing temperature.	
				One set.	Companion set.
	°C.		°C.	°C.	°C.
161.....	900	171.....	930	100	150
160.....	900	161.....	930	170	200
170.....	900	160.....	870	230	250
178.....	850	170.....	870	270	300
All others.....	800	181.....	820	350	400
		All others.....	760	450	470
				500	600
				700	

IV. APPARATUS.

The apparatus used for these experiments and the method of determining magnetic quantities have previously been described³ and need not be discussed here. After each heat treatment measurements were made of the normal induction for magnetizing forces up to 2,500 cgs units, and of the residual induction and

³ W. I. Cheney, B. S. Sci. Papers, No. 361; 1920.

coercive force from maximum magnetizing forces of 100, 200, and 1,000 cgs units. Other magnetic quantities could be calculated from the observed values. However, in the case of the annealed specimens (discussed below), measurements were also made by means of another type of apparatus.

V. MAGNETIC QUANTITIES.

Figure 1, curve 1, shows a typical magnetization curve with inductions (or flux densities) B , plotted as ordinates and the

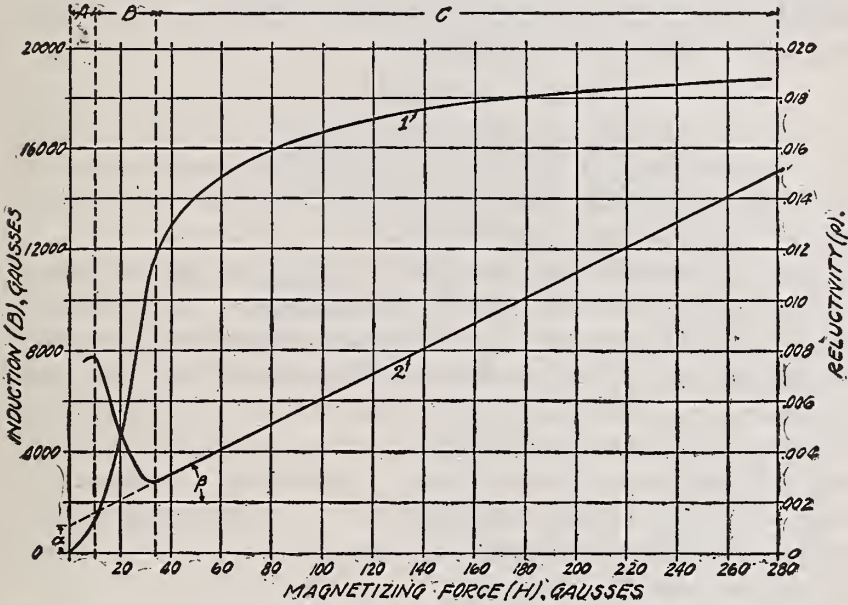


FIG. 1.—Magnetization and reluctivity curves for eutectoid carbon steel quenched in water. magnetizing forces (or field intensities) as abscissas. The permeability μ given by the relation

$$\mu = B/H$$

can be computed for various values of H and a permeability curve plotted. However, if a tangent to the $B H$ curve be drawn through the origin, the maximum permeability may be computed from the coordinates of the point of tangency.

The magnetic reluctivity ρ is defined by the relation

$$\rho = \frac{1}{\mu} = \frac{H}{B},$$

and for moderate values of H reluctivity is a linear function of H , as expressed by Kennelly ⁴ in the form

$$\rho = \alpha + \beta H,$$

⁴ Kennelly, Am. Inst. Elec. Engrs., Trans., 8, p. 485; 1891

where α and β are constants for any given material. It is found, however, that for inductions resulting from large magnetizing forces this linear relation no longer strictly holds. However, if the "metallic reluctivity" be chosen and defined thus,

$$\rho_0 = \frac{H}{B-H},$$

where $B-H$ is called the "metallic induction,"⁵ and is the magnetic flux carried by the molecules of the magnetic material not including the flux carried by the space occupied by the material, it is found that the linear relation

$$\rho_0 = \alpha + \beta H$$

does hold throughout the entire range. Curve 2, Figure 1, shows the "metallic reluctivity" ρ_0 plotted against the magnetizing force H . Throughout the remainder of the paper the word "reluctivity" refers to the metallic reluctivity.

As is well known, there are three stages in the process of magnetization,⁶ as shown in Figure 1. In stage A the elementary magnets may be thought of as having been disturbed only slightly relative to the original condition of stable equilibrium. In stage B there is a sudden swinging of the elementary magnets into position of alignment with the direction of the magnetizing force, and magnetism is acquired with considerable readiness. In stage C there is a continuous approach toward perfect alignment, and a condition of "saturation" is finally reached if the value of H be great enough.

From curve 2 it is readily seen that the reluctivity line shows the three stages even better than the magnetization curve. The linear relation

$$\rho_0 = \alpha + \beta H$$

applies only to stage C. The constant α , which is the intercept on the axis of ordinates, is called the "coefficient of magnetic hardness," and β , which is the slope, is the reciprocal of the saturation value of the "metallic induction."

The intensity of magnetization I and the susceptibility K are found from the relations

$$I = \frac{B-H}{4\pi}$$

$$K = \frac{I}{H}.$$

⁵ C. P. Steinmetz, *Gen. Elec. Rev.*, 20, pp. 135-141; 1917.

⁶ Ewing, *Magnetic Introduction in Iron and Other Metals*.

It follows at once that

$$\frac{1}{K} = 4\pi \rho_0 = \alpha' + \beta'H.$$

β' here is the reciprocal of the saturation intensity of magnetization. It is therefore more convenient to plot $1/K$ instead of ρ_0 against H .

Two other quantities which are of importance are the residual induction B_r —i. e., the induction which remains (in a closed magnetic circuit) after the magnetizing force has been removed—and the coercive H_c —i. e., the negative magnetizing force necessary to reduce the residual induction to zero.

VI. EXPERIMENTAL RESULTS.

1. HARDENED AND TEMPERED SPECIMENS.

After the specimens were hardened the induction B was observed for different values of the magnetizing force up to values of $H = 2,500$. The magnetization curve and the $1/K$ curve were plotted, and the other magnetic data computed therefrom. The residual induction and coercive force were measured from maxima of 100, 200, and 1,000 in H . This procedure was repeated after each new heat treatment. Unfortunately, it was found upon microscopic analysis that some of the specimens were not completely hardened, thus introducing variables which would make it difficult to interpret magnetic data, since magnetic measurements are more sensitive to slight metallographic differences than almost any other method. Owing to the small amount of the material available it was not possible to repeat these heat treatments and the accompanying magnetic tests, which must be postponed until more material can be prepared.

Specimens of four different compositions—namely, 0.32, 0.39, 0.88, and 0.96 per cent carbon—which were properly hardened and are structurally homogeneous are included. The data are summarized in Table 3 and plotted in Figures 2–9, inclusive, which show the variations produced in magnetic characteristics by tempering the hardened steel. The results obtained for the two comparison specimens, \odot and \times , are shown. In two cases only one specimen was available.

TABLE 3.—Variation of Magnetic Properties of Hardened and Tempered Specimens With the Drawing Temperature.

Heat treatment.	Specimen No.	Percentage carbon.	Magnetic properties. ¹							
			B_m-1	B_m-2	H_c	B_r	$\frac{B_m \times H_c}{1,000}$	μ_m	I_m	α
Quenched, but not drawn.....	170B..	.32	16,470	21,450	18	12,950	386.5	333	{ 1,660 1,520	.014 .010
	175B..	.88	7,990	17,100	56	7,700	958	80	{ 1,446 1,390	.100 .080
	174B..	.96	8,990	17,780	44	7,900	783	93.4	{ 1,510 1,404	.103 .062
Drawn to 100° C....	170B..	.32	16,240	21,200	21	12,300	445.5	317	{ 1,610 1,510?	.016 .010
	175B..	.88	9,870	18,100	43	8,100	778.4	107	{ 1,500 1,430	.070 .055
	174B..	.96	6,800	16,490	47	7,350	775.8	67.5	{ 1,390	.090
Drawn to 170° C....	170B..	.32	16,290	21,250	19.5	12,550	414.5	339	{ 1,640 1,410	.015 .089
	175B..	.88	8,510	17,050	48	7,710	819	86.5	{ 1,364 1,270	.070 .081
	174B..	.96	8,200	15,490	44	6,750	682	86.6	{ 1,218	.068
Drawn to 230° C....	170B..	.32	16,790	21,520	19	13,520	409	38.1	{ 1,650	.010
	175B..	.88	12,950	19,720	41	10,220	809	158.5	{ 1,540	.032
	174B..	.96	12,250	18,690	36	9,150	673	153	{ 1,470 1,420	.038 .030
Drawn to 270° C....	170B..	.32	17,030	21,790	16	13,550	348.8	462.5	{ 1,674	.010
	175B..	.88	15,400	21,040	27	10,900	568.3	266	{ 1,680	.020
	174B..	.96	13,600	19,240	31	9,900	596	202	{ 1,510 1,484	.027 .023
Drawn to 350° C....	170B..	.32	17,300	21,540	15	14,100	323.2	472	{ 1,660	.011
	175B..	.88	16,830	20,720	24	13,780	498	319.5	{ 1,596	.011
	174B..	.96	14,900	19,640	32	11,740	628.5	240	{ 1,526 1,480	.023 .020
Drawn to 450° C....	170B..	.32	17,350	21,440	14	15,300	-----	-----	-----	-----
	175B..	.88	16,290	20,420	30	14,580	611.5	262	{ 1,590 1,480	.020 .008
	174B..	.96	14,550	19,240	34	12,500	654	199	{ 1,520 1,470	.040 .018
Drawn to 500° C....	170B..	.32	16,750	21,000	14	15,060	294	551	{ 1,620 1,440	.014 .005
	175B..	.88	15,530	19,820	28	14,480	556	276	{ 1,550 1,500	.028 .014
	174B..	.96	14,180	18,740	29.5	12,800	552.5	255	{ 1,468 1,406	.032 .018
Drawn to 700° C....	170B..	.32	16,780	20,940	8	15,000	167.5	915	{ 1,616 1,400	.020 .002
	175B..	.88	15,450	19,840	14	13,800	278	521.5	{ 1,560 1,340	.020 .005
	174B..	.96	13,880	18,360	15.5	12,220	285	390	{ 1,450 1,336	.038 .013
Quenched, but not drawn.	170C..	.32	16,040	21,680	20	12,860	433.6	290	{ 1,676	.015
	198B..	.39	16,120	21,630	19	12,450	411.5	303.5	{ 1,670	.015
	175C..	.88	8,000	17,080	54	7,700	923	80.5	{ 1,440 1,386	.095 .073
Drawn to 150° C....	170C..	.32	16,570	21,660	15	12,840	325	346	{ 1,670	.015
	198B..	.39	15,850	20,940	16	12,000	335.3	306	{ 1,746 1,584	.028 .014
	175C..	.88	8,130	16,840	56	7,500	944	81.5	{ 1,414 1,320	.098 .070
Drawn to 200° C....	170C..	.32	16,510	21,440	21	12,900	451	354	{ 1,658	.015
	198B..	.39	16,310	21,440	20.5	12,500	440	332	{ 1,660	.017
	175C..	.88	7,800	17,140	51	8,000	874	85.7	{ 1,408	.078
Drawn to 250° C....	170C..	.32	17,050	21,740	16	13,100	348	388	{ 1,674	.015
	198B..	.39	16,950	21,740	18.5	12,800	402.5	370	{ 1,668	.018
	175C..	.88	14,080	20,340	39	11,000	794	182	{ 1,580	.025

¹ B_m-1 refers to inductions corresponding to $H=100$ cgs units. B_m-2 refers to inductions corresponding to $H=1,000$ cgs units.

TABLE 3.—Variation of Magnetic Properties of Hardened and Tempered Specimens With the Drawing Temperature—Continued.

Heat treatment.	Specimen No.	Per-centage carbon.	Magnetic properties.							
			$B_m-1.$	$B_m-2.$	$H_c.$	$B_r.$	$\frac{B_m \times H_c}{1,000}$	$\mu_m.$	$I_m.$	$\alpha.$
Drawn to 300° C.....	170C..	0.32	17,170	21,520	16	13,420	344.6	425	1,650	0.011
	198B..	.39	17,130	21,740	18	13,340	391.5	400	1,680	.012
	175C..	.88	16,450	20,660	27.5	13,120	502	292	1,596	.011
Drawn to 400° C.....	170C..	.32	17,270	21,540	16	14,760	345	477	1,660	.010
	198B..	.39	17,180	21,420	16	14,360	343	458.5	1,650	.011
	175C..	.88	16,550	20,340	30	14,060	611	289.5	1,540	.008
Drawn to 470° C.....	170C..	.32	17,250	21,440	16	15,100	343.2	514	1,576	.016
	198B..	.39	17,080	21,340	18	14,940	384	452.5	1,480	.012
	175C..	.88	15,850	20,140	32	14,600	645	262	1,396	.003
Drawn to 600° C.....	170C..	.32	17,230	21,490	10	15,350	214.9	834	1,562	.016
	198B..	.39	16,950	21,460	10	15,080	214.6	656.5	1,500	.006
	175C..	.88	15,540	20,020	20.5	14,280	411	368	1,660	.014
									1,450	.010
									1,680	.020
									1,540	.010
									1,573	.022
									1,428	.014

The curves shown in Figures 2 and 3 are typical of the relation between the maximum induction B_m and the tempering temperatures used. It will be observed for the high carbon there is a very rapid rise in the induction for the drawing temperature interval 200 to 250° C. For the 0.32 and 0.39 per cent carbon, in which case the dissolved carbon was very low, the change is less marked.

In the case of the induction for a magnetizing force of 100 cgs units it is to be noted that a maximum is reached in the neighborhood of 350° C., whereas in the case of the induction for $H = 1,000$ the maximum occurs at a somewhat lower temperature. Furthermore, the induction for $H = 1,000$ shows a much less pronounced change between 200 and 250° C. than the induction for $H = 100$. When the test specimens are magnetized by a force of 1,000 cgs units, the condition of saturation is more nearly approached and the differences in the magnitude of the induction are less marked.

Figure 4 shows the residual induction B_r (for $H = 1,000$) plotted as ordinates and drawing temperatures as abscissas. Here, as in Figure 3, there is a rise between 200 and 250° C., but here it continues through a greater drawing temperature interval, the maximum value being reached in most cases in the neighborhood of 450 or 500° C. After the maximum has been reached the decrease in magnitude (for the light-carbon steels) is more pronounced than in the case of the maximum induction.

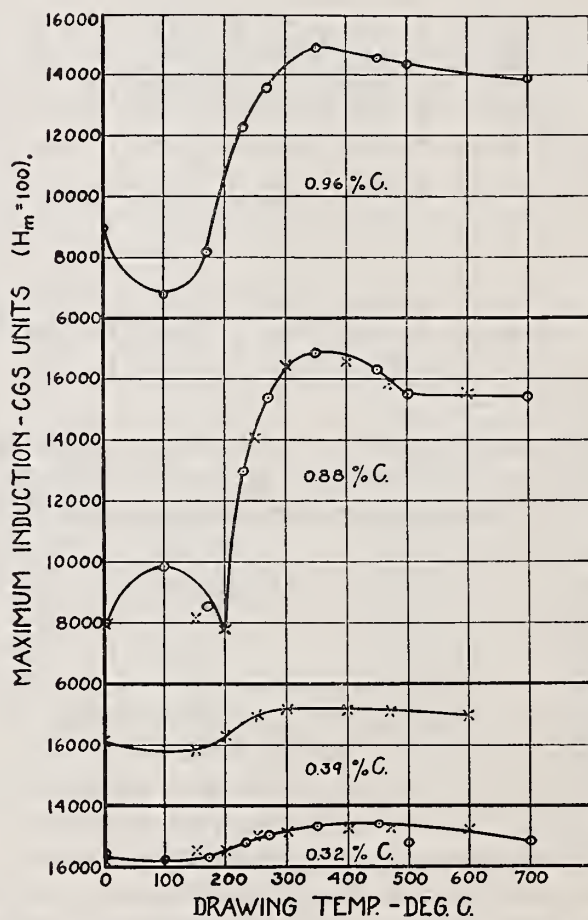


FIG. 2.—Variation of induction for a magnetizing force of 100 cgs units with the drawing temperatures.

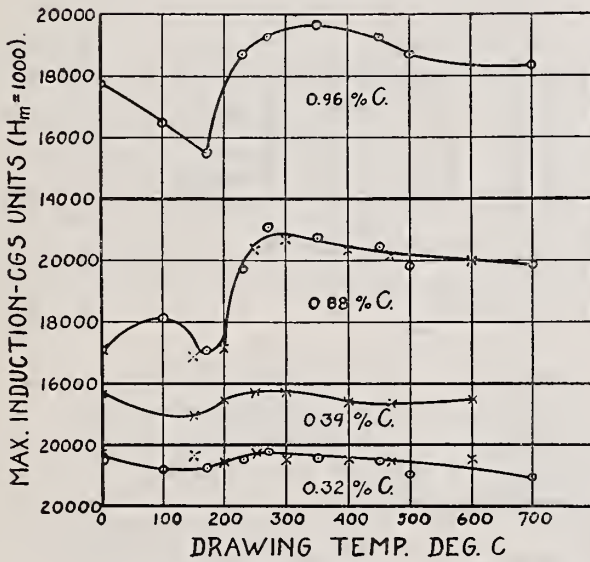


FIG. 3.—Variation of induction for a magnetizing force of 1,000 *cas* units with the drawing temperatures.

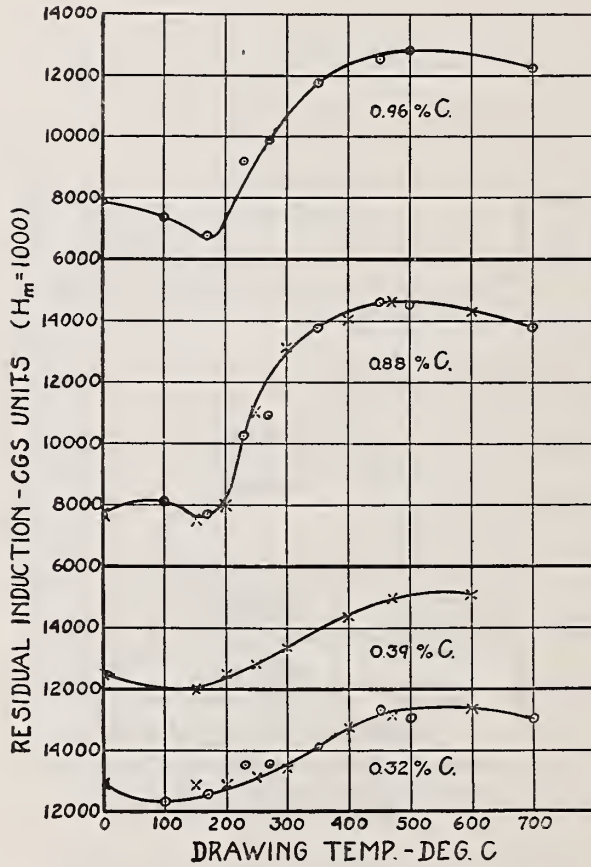


FIG. 4.—Variation of residual induction from a magnetizing force of 1,000 cgs units with the drawing temperatures.

Another quantity which is of importance in detecting transformations in alloys as the drawing temperature is raised is the coercive force. The coercive force, in general, corresponds more or less to changes in mechanical hardness.⁷ In Figure 5 the coercive force measured from a maximum magnetizing force of 1,000 is shown plotted against the drawing temperature. The coercive force for the higher percentage of carbon is great in the quenched condition but falls off with higher drawing temperatures. A minimum is reached in the neighborhood of 250° C. The values increase until another maximum is reached at 450 or 470° C., making a cusp in the curve. This effect was also found by Maurer⁸ in experiments on hardened carbon steels. Hardness curves taken by Maurer did not show this cusp, however.

An important consequence of magnetic hysteresis is that work is required to change magnetization, and therefore there is a dissipation of energy. In a cyclic process the area of the hysteresis loop measures the amount of energy thus dissipated.⁹ In the present investigation the whole hysteresis loop was not traced, but only three points of it located, namely, maximum induction B_m , residual induction B_r , and the coercive force H_c . However, a rough approximation to the area of a hysteresis loop¹⁰ is given by the equation

$$\text{Area of loop} = 4 \times H_c \times B_m.$$

This value is too large for materials of low permeability and too small for material of high permeability, but the error in either case is probably within 15 per cent. Hence, if the product $B_m \times H_c$ be plotted against the drawing temperature, the curve will indicate the general trend of energy loss.

Gebert¹¹ has shown that there is a close relationship existing between the product $B_m \times H_c$ and the tensile strength and between $B_m \times H_c$ and the Brinell hardness number.

Figure 6 shows this product plotted against the drawing temperatures as the independent variable. The cusp in the curve near 450–470° C. is even more pronounced here than in the case of the coercive force.

As previously pointed out,¹² the third stage of the reluctivity line, or, equally as well, of the reciprocal of the susceptibility is

⁷ Burrows and Fahy, A. S. T. M., Proc., 19, p. 5; 1919. C. Nusbaum, A. S. T. M., Proc., 19, p. 96; 1919.

⁸ Maurer, Rev. de Met., 5, pp. 711–750; 1908.

⁹ Ewing, Magnetic Induction in Iron and Other Metals.

¹⁰ Bureau of Standards Circular No. 17.

¹¹ Gebert, J. Am. Steel Treating Soc., June, 1919.

¹² Nusbaum, Cheney, and Scott, B. S. Sci. Papers, No. 404; 1920.

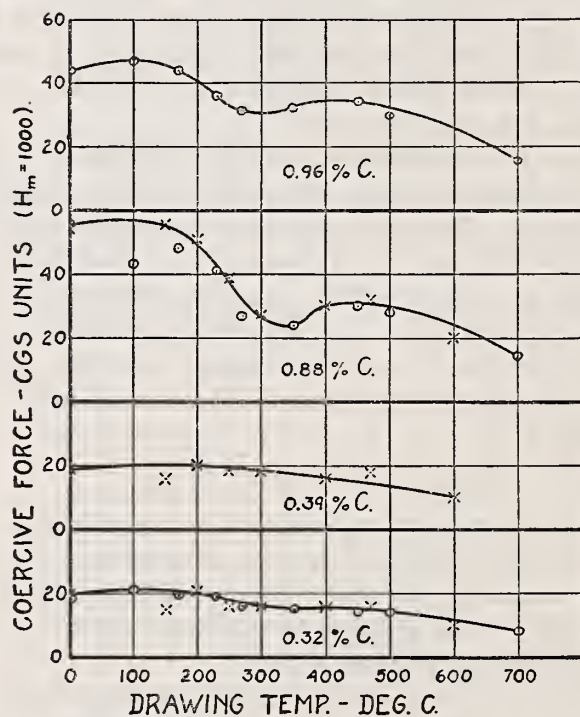


FIG. 5.—Variation of coercive force from a magnetizing force of 1,000 cgs units with the drawing temperatures.

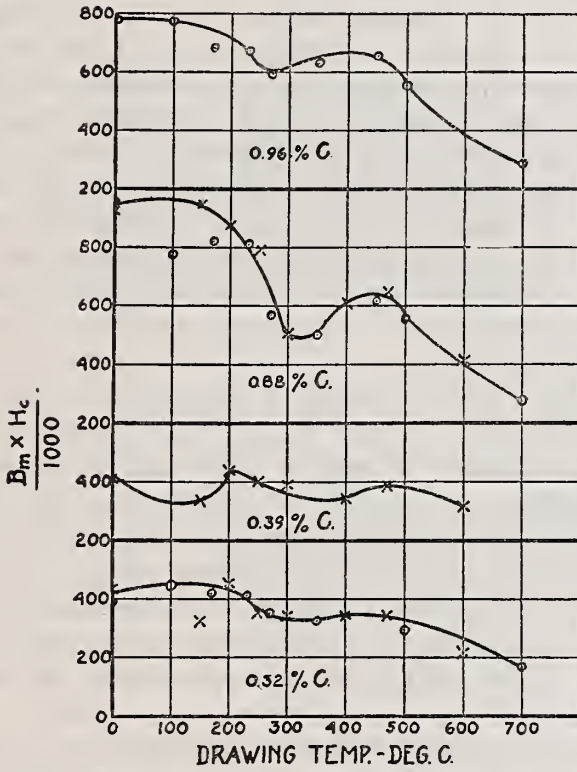


FIG. 6.—Variation of energy loss due to hysteresis with the drawing temperatures.

valuable as a means of detecting transformations in steels when carried through a series of heat treatments.

The reciprocal of the slope of this line gives the maximum intensity of magnetization or the "saturation" intensity. For homogeneous materials this $1/K H$ line is a straight line, but for materials which are not homogeneous it approximates to a straight line, but really consists of two or more linear portions, there being a distinct point where the slope changes. Thus, it follows that for lines of this character there will be two or more values of the maximum intensity of magnetization—one for each straight-line portion. B. O. Peirce¹³ has pointed out that the value of the maximum intensity of magnetization I_m obtained from the lower portion of the line is less than the true saturation value, while I_m calculated from the upper portion where the slope is somewhat different is somewhat in excess of the true saturation value. As pointed out by Steinmetz¹⁴ and verified experimentally by Ball,¹⁵ this change in slope is indicative of the presence of two or more constituents of differing degrees of magnetic hardness, which reach the maximum intensity of magnetization for different values of the magnetizing force H .

These values of I_m as computed from slopes of $1/K H$ lines are plotted in Figure 7 with the drawing temperature as the independent variable. It will be noted that for alloys of low and intermediate percentages of carbon, from the hardened condition up to that drawn to 170° C., there are two values of I_m resulting from a bend in the $1/K H$ line. From 200 to 350° C., inclusive, the maximum intensity of magnetization is single valued. From 400 to 700° C., inclusive, there are again two values of I_m . For the 0.96 per cent carbon there are two values of I_m throughout.

Perhaps the variations with heat treatment can be shown to better advantage by making use of the intercept α of the $1/K H$ line on the axis of ordinates. This intercept value is frequently called the coefficient of "magnetic hardness" of the material. Such curves are shown in Figure 8.

The above-mentioned properties refer, primarily, to conditions of stability; i. e., the "third stage" (Fig. 1). Most of these properties, however, do not show the ease with which this condition of stability is reached. That is, maximum permeability

¹³ Peirce, B. O., *Am. Acad. Arts and Sci., Proc.*, 49, pp. 117-146; 1913.

¹⁴ Steinmetz, *Gen. Elec. Rev.*, 20, p. 135; 1917.

¹⁵ J. D. Ball, *J. Frank. Inst.*, 181, p. 481; 1916.

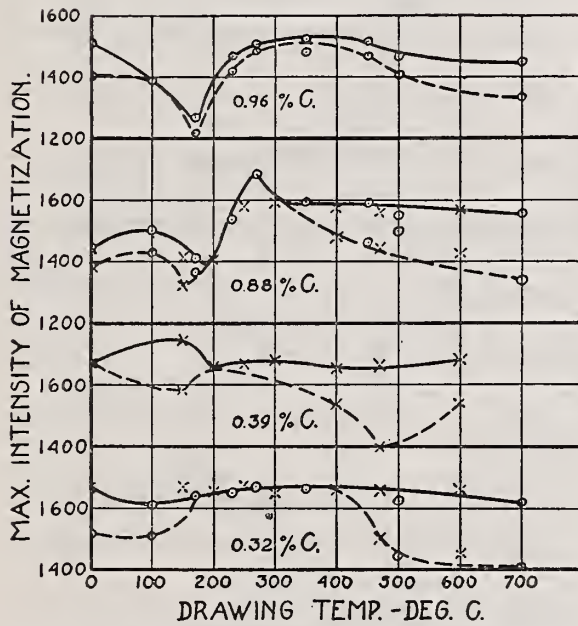


FIG. 7.—Variation of maximum intensity of magnetization with the drawing temperatures.

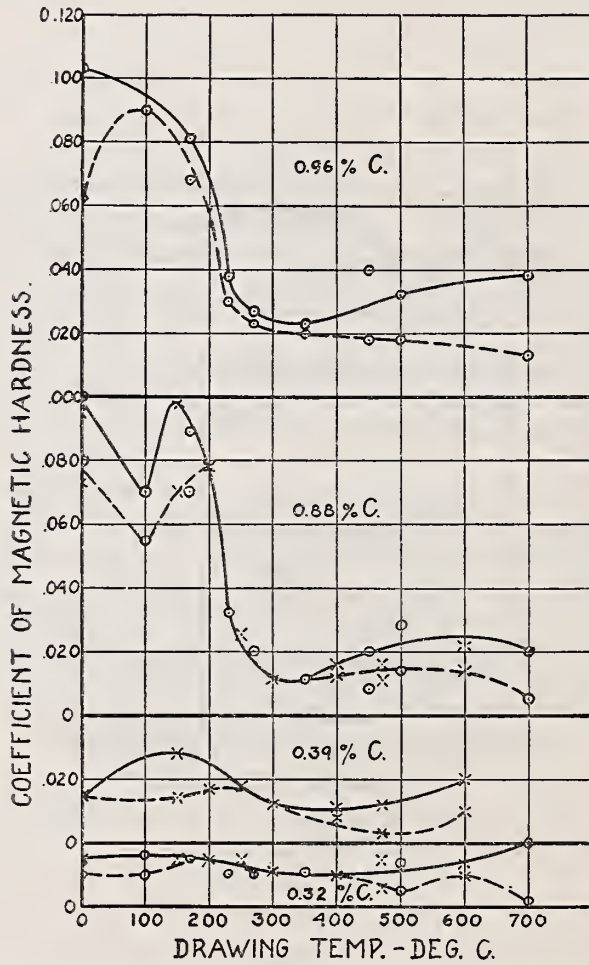


FIG. 8.—Variation of the coefficient of magnetic hardness with the drawing temperatures.

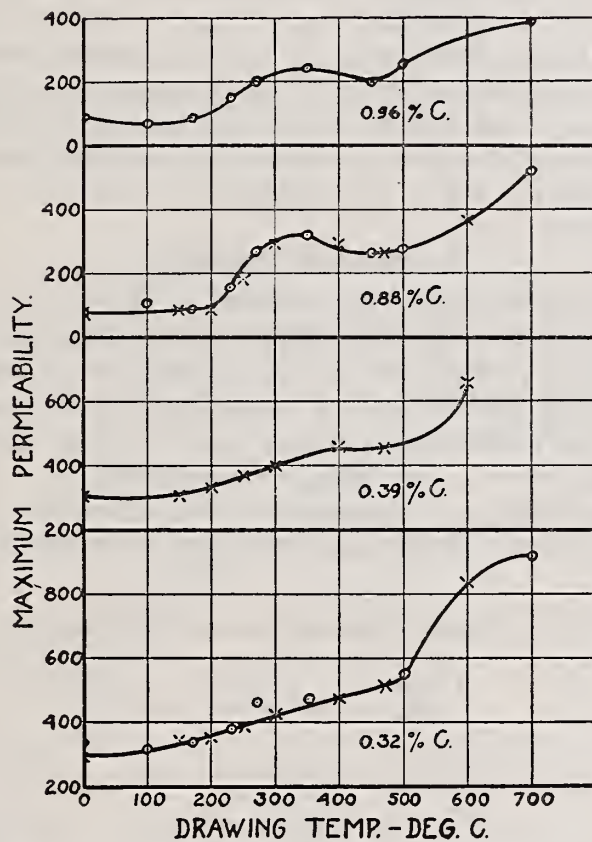


FIG. 9.—Variation of maximum permeability with the drawing temperatures.

may be reached for larger or smaller values of the magnetizing force without any appreciable change in the maximum intensity of magnetization. It was found in these experiments that, in general, the stage B (Fig. 1) of the magnetization curve became crowded more and more closely toward the origin as higher drawing temperatures were reached. The maximum permeability, therefore, increased in magnitude as it occurred for smaller values of the magnetizing force. Figure 9 shows this increase in the maximum permeability μ_m with the drawing temperature.

It is to be noted that while the other magnetic quantities show little change in the case of the 0.32 per cent carbon alloy, there is an increase of about 200 per cent in the maximum permeability. The permeability curves for the high carbon show the cusp near 450–470° C.

2. ANNEALED SPECIMENS.

The specimens which were annealed as described above were so much softer than the other heat-treated specimens and reached the maximum permeability for so small values of the magnetizing force that the method used for measuring magnetic quantities in intense fields which is not very accurate for very low magnetizing forces, say, below 50 cgs units, is consequently not satisfactory for determining μ_m . Measurements were therefore made by means of entirely different apparatus suitable for low magnetizing forces.¹⁶

TABLE 4.—Magnetic Properties of Annealed Iron-Carbon Alloys.

No.	Percent- age carbon.	B_m $H=150$	B_c $H=150$	H_c $H=150$	μ_m	I_m	α
171A.....	0.018	18,740	11,680	3.1	5,320	1,703	0.0104
161A.....	.14	18,240	9,980	3.3	2,990	1,722	.0232
						1,504	.0023
160A.....	.23	18,010	10,010	4.5	2,090	1,688	.0133
						1,464	.0049
170A.....	.32	17,790	9,830	5.0	1,560	1,670	.0147
						1,355	.0017
181B.....	.52	17,310	9,410	6.1	1,180	1,626	.0186
						1,436	.0080
175A.....	.88	16,050	10,610	8.5	830	1,583	.0316
						1,363	.0085
169A.....	1.28	15,130	10,730	8.3	880	1,537	.0530
						1,419	.0227
172A.....	1.32	14,990	10,530	7.5	920	1,507	.0431
						1,385	.0173
168A.....	1.55	14,190	9,390	7.5	900	1,528	.0579
						1,463	.0367
						1,263	.0124
159A.....	1.60	13,850	8,990	11.0	470	1,534	.0537
						1,264	.0225

Magnetization curves (Fig. 10) show a decided change in the steepness of the second stage of the curve, and hence a decided

¹⁶ M. F. Fischer, B. S. Sci. Papers, No. 458.

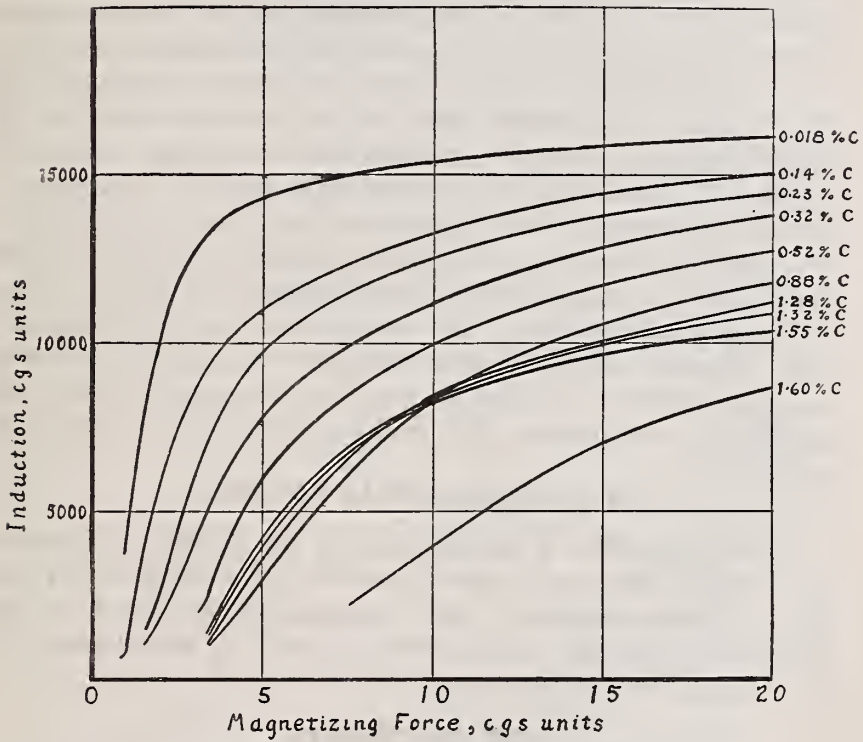


FIG. 10.—Normal induction curves for specimens annealed in vacuo.

change in the maximum permeability (Fig. 11) with a change in the carbon content. Hysteresis data measured from a maximum magnetizing force of 150 cgs units were also taken and, together with the induction corresponding to the same magnetizing force, are plotted in Figure 11 and tabulated in Table 4. The coercive force here shows a maximum for the 1.6 per cent carbon alloy.

The graphs for the maximum intensity of magnetization and for the intercept values or "magnetic hardness" were computed from the $1/K H$ lines resulting from measurements carried to large magnetizing forces. It will be noted that there are two values for the intensity of magnetization and for the coefficient of magnetic hardness, except for the nearly pure iron where there is but one value, and for the 1.55 per cent carbon where there are three values. The general trend of the maximum intensity of magnetization is a decrease with the carbon content. This corresponds to what Hadfield and Hopkinson found.¹⁷ Waggoner,¹⁸ on the other hand, found a minimum value near the eutectoid. Waggoner, however, was not using the saturation value but rather the intensity of magnetization corresponding to a definite value of the magnetizing force. His curves show that this minimum value becomes less pronounced the higher the magnetizing force, and it is probable that had he been able to magnetize all of his specimens to saturation this minimum would have quite disappeared.

VII. MICROSCOPICAL ANALYSIS.

Micrographs, all at a magnification of 500 diameters, represent the average structural condition shown by etching in a 5 per cent alcoholic picric acid. Such micrographs were made of the quenched specimens, those drawn to 270° C., those drawn to 700° C., and the annealed specimens.

VIII. DISCUSSION.

The magnetic tests indicate three distinct ranges: (1) Up to drawing temperature 230° C., (2) between 250 and 450° C., and (3) 470-700° C., in which the constituents differ in their magnetic characteristics (Figs. 2-9).

As pointed out previously,¹⁹ an abrupt change of slope in the $1/K H$ line when the steel is in the quenched condition may be due to the fact that the steel is strained during the quenching process,

¹⁷ Hadfield and Hopkinson, *J. Inst. Elec. Engr.*, **46**, pp. 235-284; 1911.

¹⁸ C. W. Waggoner, *Phys. Rev.*, **35**, pp. 58-65; 1912.

¹⁹ Nusbaum, Cheney, and Scott; *B. S. Sci. Papers*, No. 404; 1920.

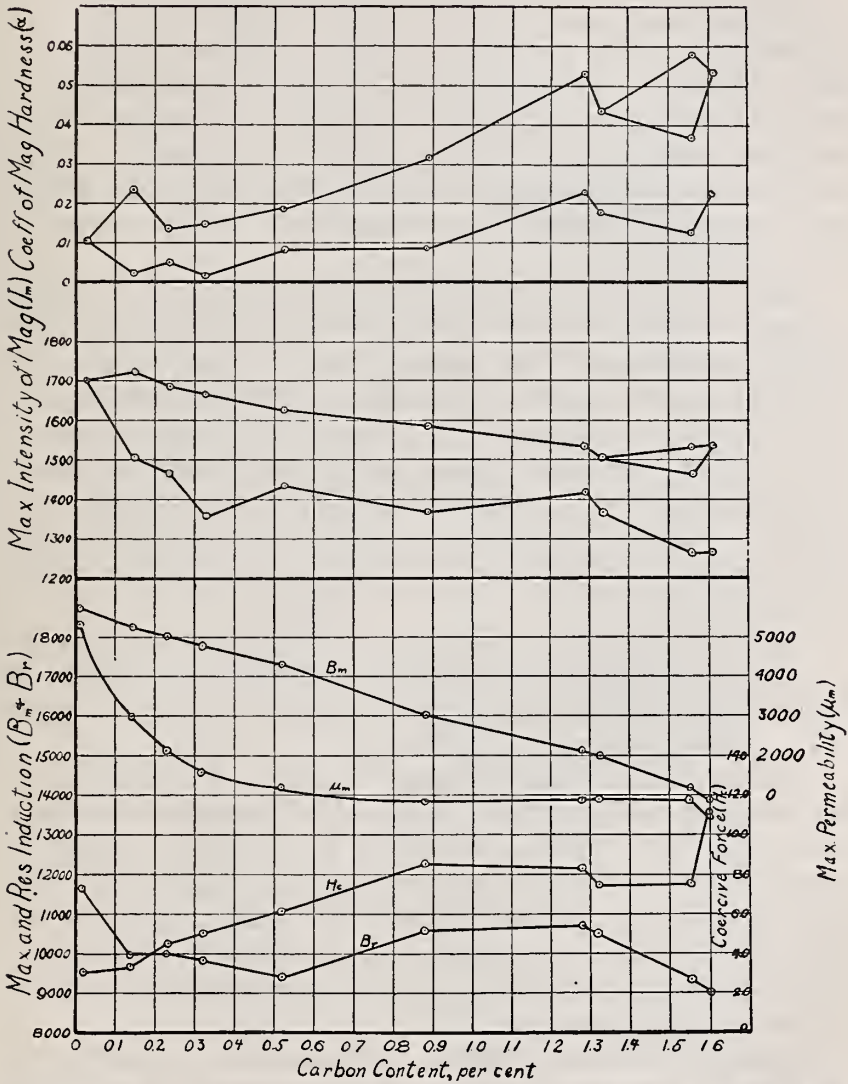


FIG. 11.—Variation of various magnetic quantities with the carbon content for the annealed specimens.

and that there are thus stresses set up in the material, or it may signify the presence of two different constituents. The specimens which have been discussed herein were homogeneously martensitic.

In case of the specimens which have been drawn to 270° C. the only alloy which has two values of the "saturation" intensity of magnetization is the 0.96 per cent carbon. Microscopic analysis shows only one constituent, namely, tempered martensite for the 0.32 and 0.39 per cent carbon, but for the 0.88 per cent carbon tempered martensite and troostite appear to be present. However, this tempered martensite may really be troostite, for Scott²⁰ has shown that martensite is transferred to troostite on tempering above 260° C.

Honda²¹ has shown that cementite is present in this region, although ultramicroscopic. Under such conditions it is distributed uniformly in fine particles not occurring as separate crystals, and its magnetic properties are masked by those of other constituents of greater size. On the other hand, if cementite is present in sufficiently large masses, its magnetic properties become apparent and it will behave as a separate magnetic constituent. This is evidently the case in the 0.96 per cent carbon alloy (drawn to 270° C.) where an abrupt change of slope occurs in the $1/KH$ line.

When the specimens have been drawn to 700° C. they all contain two constituents—cementite and ferrite. It might be predicted, therefore, that there would in these cases be two values of I_{\max} , which was found to be true.

When the alloys (not including the nearly pure iron) are in the annealed condition there appear to be present two constituents (Fig. 12). The magnetic data agree with this, with the exception of the 1.55 per cent carbon, which appears to have three values of I_{\max} instead of two. Why there should be two points in the $1/KH$ line where the slope changes the writer is unable to offer any suggestion, and further investigation is necessary to clear up the matter.

Figure 12a is a micrograph of nearly pure iron. This has the characteristic structure of α iron and also shows the persistence of the structure of the γ iron which existed at the annealing temperature. The $1/KH$ line for this specimen shows no bend but is a straight line with a slight hump in the neighborhood of $H=200$.

²⁰ H. Scott, B. S. Sci. Papers No. 396; 1921.

²¹ Honda, Tohoku University Reports, 6, p. 149; 1917.

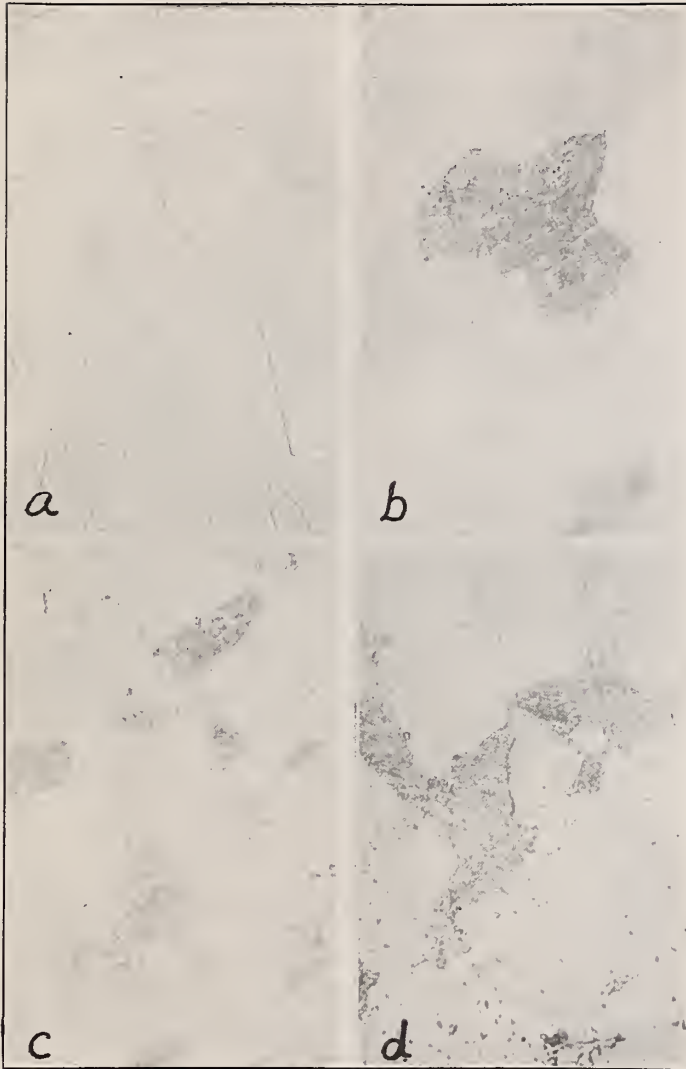


FIG. 12.—Micrographs of iron-carbon alloys annealed in *vacuo*

- a*, 0.018 per cent carbon, double structure of α and γ iron
- b*, 0.14 per cent carbon, pearlite and ferrite
- c*, 0.23 per cent carbon, pearlite and ferrite
- d*, 0.32 per cent carbon, pearlite and ferrite

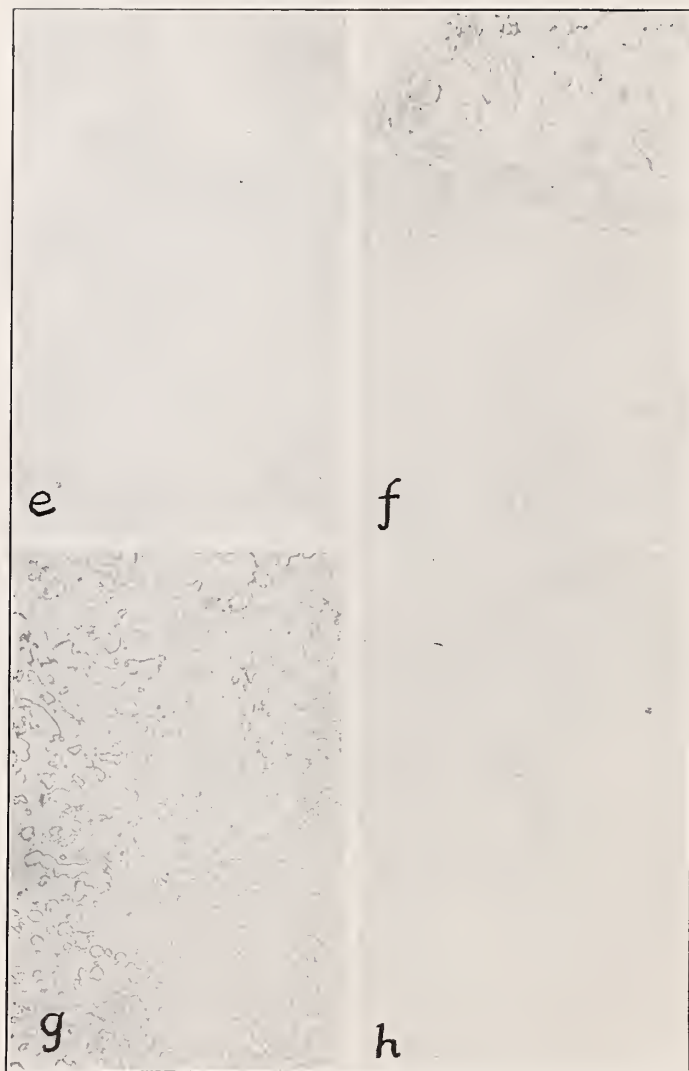


FIG. 12.—Micrographs of iron-carbon alloys annealed in vacuo—
Continued

- c*, 0.52 per cent carbon, pearlite and ferrite
- f*, 0.88 per cent carbon, pearlite approaching divorced phase
- g*, 1.28 per cent carbon, cementite and ferrite
- h*, 1.32 per cent carbon, cementite and ferrite

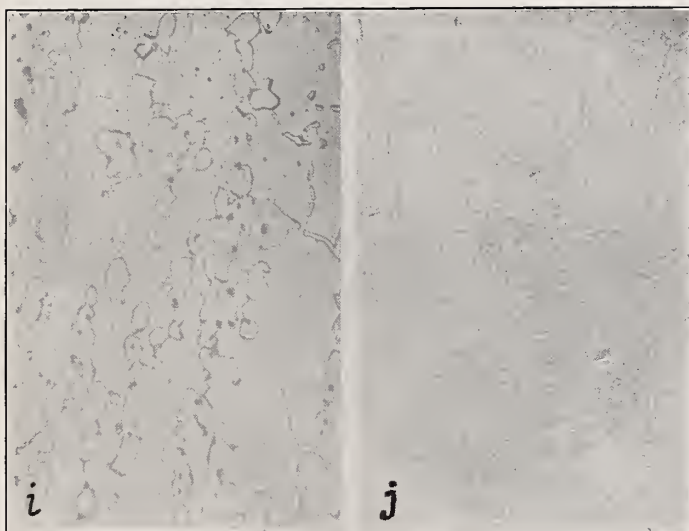


FIG. 12.—Micrographs of iron-carbon alloys annealed in vacuo—
Continued

i, 1.55 per cent carbon, cementite and ferrite

j, 1.60 per cent carbon, cementite (network and islands) and ferrite

IX. SUMMARY.

In this paper data are presented showing the effect of heat treatment on the magnetic properties of a series of pure iron-carbon alloys. The main features of the paper may be summarized as follows:

1. The alloys hardened by quenching in oil and water from suitable quenching temperatures when drawn back to successively higher temperatures show certain magnetic transformations: (a) There is a rapid rise in the induction (H constant) between 200 and 250° C., which finally reaches a maximum at some definite temperature and gradually decreases. (b) There is a similar trend of the residual induction but less rapid rise, with a delayed maximum and a somewhat more rapid descent following. (c) Marked changes occur in the coercive force which may be considered as indicative of the mechanical hardness of the material. The greatest decrease in the coercive force is between 200 and 300° C. A cusp in the curve occurs in the neighborhood of 470° C., indicating a structural change of the material at this temperature. (d) Similar changes are shown by considering the product $B_m \times H_c$, which is proportional to the dissipation of energy owing to hysteresis. (e) The reluctivity relationship is employed to compute the saturation intensity of magnetization. In some cases this maximum value of the intensity was single valued, in some cases double valued. Micrographs of the quenched specimens of those drawn to 270° C. and those drawn to 700° C. confirmed in the majority of cases the fact that the number of values of I_m represents the number of constituents present in the material. (f) The intercept value of the reluctivity line also serves to indicate the "magnetic hardness." (g) Values of the maximum permeability show very great differences for certain alloys as compared with small differences in other magnetic quantities. This is due to changes in the second stage of the process of magnetization.

2. For the annealed alloys: (a) Magnetization curves (for low inductions) show a decided change in the steepness of the curve in the second stage, and hence a change in the maximum permeability, with a change in the percentage of carbon content. (b) The coercive force has a maximum for the highest carbon used. (c) The intensity of magnetization, which was double except for pure iron, where it was single valued, and the 1.55 per cent carbon, where it was triple valued, decreased with an in-

crease in the carbon content. (d) Micrographs confirmed the number of constituents which might be predicted from the number of values of I_m in all cases except the 1.55 per cent carbon.

3. The experiments bring out the following points: (a) The sensitiveness of magnetic quantities to any slight changes of metallographic structure as a result of heat treatment is marked. (b) The necessity of very accurate control in heat treating specimens for a study of their magnetic properties is clear. (c) Further experiments are necessary before any definite quantitative relationship can be established between the various magnetic quantities and the heat treatment or between magnetic quantities and the chemical composition. (d) All magnetic quantities must be considered in studying the effect of heat treatment and chemical composition.

In conclusion the writer wishes to acknowledge the assistance of Messrs. Neville and Cain, who prepared the alloys; of Messrs. Waltenberg and Derry for forging; of T. G. Digges, who did the heat treating; of Messrs. Rawdon and Sillers for the microscopic analysis; of M. F. Fischer, who made measurements at low inductions; of H. Scott and Dr. C. Nusbaum for valuable suggestions regarding the most suitable temperatures for quenching, annealing, and tempering; and of R. L. Sanford, chief of the magnetic laboratory, at whose suggestion the investigation was undertaken, and who has given the writer every facility and opportunity for carrying the work through to completion.

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WASHINGTON, July 24, 1922.