THE EFFECT OF CHANGES IN TOTAL CARBON AND IN THE CONDITION OF CARBIDES ON THE MAGNETIC PROPERTIES OF STEEL

By Arthur W. Smith, Edward D. Campbell and William L. Fink

Abstract

Variation of magnetic properties of a carbon steel and a chrome steel with per cent carbon, for annealed and quenched samples.—Two series of small steel bars were prepared with carbon varying from .01 to 1.17 per cent, one from Armco iron (total impurity .1 per cent or less), the other from chrome magnet steel with composition in per cent: Cr 2.23, Mn .24, Si .25, Ni .12, Cu .08, S .03, P .03. The carbon content was obtained and controlled by maintaining the bars along with steel of different carbide content until equilibrium was attained in hydrogen at 950°C. *Magnetization curves* are given for the different bars. The *minimum reluctivity R* (reciprocal of the *maximum permeability*) is found to be a linear function of the carbon content for hardened steels, to 0.8 per cent C. For annealed carbon steels, *R* increases somewhat faster than the per cent C and for annealed chrome steels *R* shows a maximum at about .5 per cent and a minimum at about 0.8 per cent C. The magnetic intensity necessary for saturation varies in the same way as *R*.

Magnetic potentiometer method of determining normal magnetization curves for short bars.—The bar and yoke apparatus used is arranged so that the small bar forms part of a closed magnetic circuit, and the magnetomotive force is distributed so as to be proportional to the reluctances of the bar and the yoke, respectively, by use of a magnetic potentiometer which consists of a solenoid of several thousand turns, with soft iron end plates which make contact with two points of the circuit. The magnetic flux was measured with a test coil connected to a dead beat ballistic galvanometer, by noting the deflection produced by reversing the flux. A special reversing rheostat was used to vary the current by 120 definite steps so as to give a definite magnetic cycle. Tested with samples of annealed Armco iron, this apparatus gave the same curve as the standard ring method.

IT has been recognized for many years by chemists and metallurgists that carbon is the essentially characteristic element which distinguishes all steel from iron, and that carbon in steel occurs chemically combined as a carbide either of iron alone or with more or less of the iron replaced by other elements. Some of these, such as chromium, tungsten, molybdenum, vanadium, and manganese, form with iron double carbides which have a very marked difference in their influence on the properties of steel from those produced by the carbides of iron alone. The properties of steel are also influenced by the heat treatment to which the steel has been subjected. If the steel is heated above the critical range, the carbides pass into solution and may be largely retained in this condition

by rapid cooling through the critical range, as in water hardening. If, however, the metal is slowly cooled through the critical range, as in annealing, most of the carbides precipitate, leaving a relatively small proportion of the carbides in solution. The concentration of carbides remaining in solution after annealing will depend on the total carbon content and the constitution of the resulting carbides.

The effect of changes in carbide concentration on the magnetic properties of some heat treated carbon steels has been studied[1] by means of a special magnetic balance designed by one of the authors. The object of the present investigation is to extend our knowledge of the effect of changes in carbide concentration on the magnetic properties of steel by a more precise method,[2] using a magnetic potentiometer designed by A. W. Smith.

For this work two series of small steel bars were prepared and heat treated in the chemical laboratory. One series was prepared from Armco iron, furnished by the American Rolling Mill Company, and the other from a sample of chrome magnet steel furnished by the Penn Seaboard Steel Corporation. Each series consisted of bars containing four different carbon contents. The bars of each series having the lowest carbide content were produced through decarburization by means of the action of hydrogen at 950°C.[3] The carbide content of the other bars was varied by maintaining them in a still atmosphere of pure dry hydrogen at 950°C, together with steel of different carbide content, until equilibrium had been reached.[3]

The annealing of all bars was effected by allowing them to cool from 950°C over night with the furnace in which they were prepared. The hardening was effected by suspending a number of bars for one hour in an electrically heated furnace which had been brought to the temperature from which it was desired to quench the bars, and then quenching them in a large volume of water at 25°C. The temperature of the bars at the moment of withdrawal from the furnace was measured by means of a standard platinum-platinrhodium thermocouple, the bead of which was within 2 or 3 mm of the bars under treatment. The upper half of the heating chamber in which the bars were suspended, consists of nichrome wire gauze and is surrounded with charcoal so that the bars may be maintained for any desired length of time without any sign of oxidation. Bars A, B, C, and E were quenched from 915°C while D, F, G, and H were quenched from 885°C in order to ensure homogeneity.

[1] E. D. Campbell and E. R. Johnson, Jour. Iron and Steel Inst., 1922, No. 2, p. 201

[2] Arthur W. Smith, Phys. Rev. **19**, 424 (1922)

[3] Details were reported to the Iron and Steel Institute, Autumn Meeting, Sept. 1923

The chemical composition of the steels prepared for this work is given in Table I.

Unfortunately for magnetic testing, these steels are all in the form of short bars, 15 cm in length and 6 by 6 mm in cross section. They are a part of a set comprising several hundred bars of similar dimensions

TABLE 1

Composition in weight percent of the prepared steel bars

Steel bars	C	Mn	P	S	Si	Cr	Ni	Cu
A16 and A11	.008	.011	.006	<.018				.018
B1 and B4	.33	.024	.005	.023	trace			.042
C22 and C23	.41	.016	.005	.03	trace			.045
D3	.70	.016	.005	.03	trace			.045
D5	.70	.011	.006	.018				.018
E10 and E13	.04	.24	.027	<.035	.25	2.23	.12	.084
F1	.55	.24	.027	.035	.25	2.23	.12	.084
F2	.52	.24	.027	.035	.25	2.23	.12	.084
G19 and G29	.85	.24	.027	.035	.25	2.23	.12	.084
H25 and H27	1.17	.24	.027	.035	.25	2.23	.12	.084

accumulated during the past ten years by one of the authors in the course of his researches on the constitution of steel. For magnetic testing the ring form is much better as it gives a uniform magnetic circuit and the uncertainties due to the ends of the bars do not appear.

Inasmuch as it is difficult to confine the magnetic flux to a prescribed circuit without serious leakage, it seemed best to build a bar and yoke apparatus in which the m.m.f. would be applied bit by bit along the entire circuit, being distributed over each part in proportion to the reluctance of that part. This arrangement avoids the uncertainties due to magnetic leakage.

The bar and yoke apparatus. The arrangement of the magnetic circuit is shown in Fig. 1. AB represents the bar to be tested. Each end of this bar is tightly clamped into the yoke of common iron that completes the

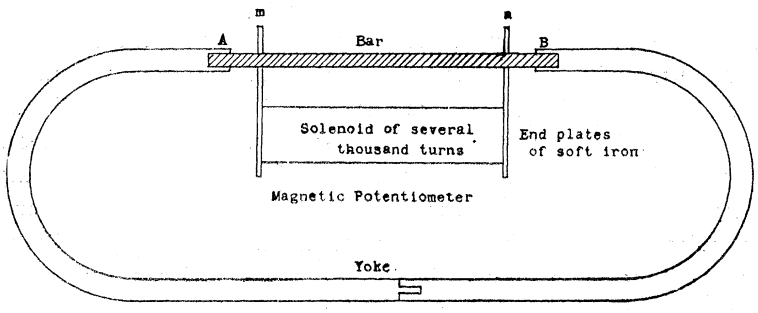

Fig. 1. Bar and Yoke, giving a closed magnetic circuit. The "magnetic potentiometer" is shown, connected to the bar.

magnetic circuit. The square bar is held by hollow square jaws that make contact for about a centimeter length along the bar. If the bar is not absolutely square, good contact is assured on at least two sides of the bar. There is another joint at the middle of the yoke. The reluctance of the circuit is thus made up of three parts, that of the bar, of the yoke, and of the joints.

The magnetizing coils. Surrounding the bar are three brass spools, a long one in the middle and a short one at each end, with a space of 3 mm at m and n, the reason for which appears below. These spools carry a uniform winding of p turns per cm, with additional turns at each side of m and n equal to the number of turns that should have been placed in these openings to make the winding uniform throughout. These coils are permanently connected in series and carry the current that magnetizes the bar.

Over the entire length of the yoke is another uniform winding with additional turns over each joint proportional to the extra reluctance at these places. The current through this winding is independent of that around the bar, and it is adjusted to the value necessary to magnetize the yoke to the same total flux as exists in the bar. Under this condition the magnetic flux is continuous through the bar and the yoke, the same as though the circuit were of uniform material and magnetized by a single current I in a uniform winding of p turns per cm.

Measurement of magnetic flux. The magnetic flux was measured by the deflection of a Leeds and Northrup high sensitivity ballistic galvanometer, arranged as a deadbeat fluxmeter and critically damped by a circuit of 70,000 ohms. When joined to a low resistance, as in the present case, the galvanometer is practically shortcircuited and it is so greatly over damped that it stands nearly at rest on any part of the scale, drifting back only slowly towards the zero position.

The test coil consisted of 50 turns of fine copper wire wound on the middle of the long brass spool before the primary winding was put on. It therefore encircles the middle of the bar and includes a minimum of the surrounding space. When the magnetic flux is reversed the galvanometer gives a quick swing and comes to rest at the end of the deflection. It is not difficult to read this position on the scale, as the drifting is very slow, but a more exact reading is taken. The scale, as seen in the reading telescope, is watched until one of the lines comes squarely under the vertical cross hair of the telescope. This coincidence can be determined more exactly than an intermediate position between two lines. At this instant the magnetic flux is reversed again, deflecting the galvanometer back to the zero position, or a little beyond. There is now no

tendency even to drift, and the reading can be determined under stationary conditions. Moreover, if there is any time lag of the magnetic flux the reading can be deferred without error until the flux has reached its full value.

The reversing rheostat. When an inductive circuit is suddenly broken it is not possible to tell how the current will vary as it dies down to zero. The spark shows the high value of the induced e.m.f. that tends to keep the current flowing, and in some cases the current may even oscillate a few times before the energy of the magnetic field is dissipated. In such a case the magnetic cycle of the iron may differ widely from the regular hysteresis loop when the current is gradually reduced to zero.

In order to avoid the possibility of this uncertainty in the cycle through which the iron is carried, and also to make the changes slowly and regularly so as to avoid any violent and sudden impulses on the galvanometer, the magnetizing current was varied by a special rheostat. By turning the movable arm of this rheostat, resistance was introduced into the circuit sufficient to bring the current to zero during the first quarter turn. At this point the next step reversed the battery connections, and then the resistance was gradually cut out of the circuit during the next quarter turn. Thus by merely swinging the arm of the rheostat through a half turn and back again, the magnetizing current is changed through one cycle from $+I$ to $-I$ and back to $+I$ in 120 steps. Each step gives a small impulse to the galvanometer which thus reaches its maximum deflection without any sudden shock. This feature is especially desirable when the galvanometer is being calibrated by reversing the current in a standard of mutual inductance.

The magnetic potentiometer. The total m.m.f. applied to the magnetic circuit is easily computed by the formula $4\pi NI$, but how much of this is used for the bar and how much for the rest of the circuit? The case is similar to that of an electric circuit composed of alternate resistances and batteries. The total e.m.f. drives the current through the total resistance, but the batteries in a given portion, AB, may not furnish all of the e.m.f. that is used in this portion of the circuit. Whether they do or not could be determined by connecting a voltmeter to A and B. If the voltmeter indicates no difference of potential between these points it shows that the fall of potential RI in this portion of the circuit is just equalized by the e.m.f. of the batteries in this portion.

The magnetic potentiometer, corresponding to the voltmeter, consists of a coil of several thousand turns of fine wire wound on a fibre core. The ends of this solenoid are supplied with flat pieces of soft iron that extend on one side far enough to be clamped against the test bar

at m and n. If there is a difference of magnetic potential between these points some flux will be shunted from the bar to the circuit through this coil,[4] and when the flux is reversed it can be detected by the galvanometer. If there is no difference in magnetic potential between two points on a magnetic circuit when a m.m.f. of $4\pi NI$ gilberts is applied to the circuit between them it shows that just this amount of m.m.f. is required to maintain the flux through this portion of the circuit. The number of gilberts per cm required along this part of the circuit is, then,

$$H = 0.4\pi pI_a$$

where pI_a denotes the number of ampere-turns per cm.

Usually the adjustment is made by setting the current around the bar at a given value, and then varying the current in the winding around the yoke until, after many reversals of both currents, there is no change of flux through the coil of the magnetic potentiometer. It is then a simple matter to shift the galvanometer connections to the test coil around the bar and measure the corresponding value of the flux through the bar.

Test of the bar and yoke. The bar and yoke method described above was compared with the standard ring method by determining the normal magnetization curves for a bar and a ring of Armco ingot iron, both of which had been annealed together so as to be as nearly alike as possible. Each method gave the same curve, even more closely than could well be expected from two samples of the same iron by either method.

Calibration of the galvanometer. The galvanometer was calibrated by means of a standard of mutual inductance, the secondary of which was kept in the galvanometer circuit. When a calibration was desired a known current was passed through the primary and reversed by means of the same reversing rheostat as was used for the bar and yoke. For the range of deflections used in this work the scale deflection is very closely proportional to the flux cut by the galvanometer circuit.

Comparison of the steels. The normal magnetization curves showing the relation between the flux density B, in maxwells per cm^2, and the magnetic intensity H, in gilberts per cm, are given in Figs. 2, 3, 4 and 5. These curves are drawn accurately to scale, and the observed points are all covered by the width of the line.

An increase in the percentage of carbon increases the amount of the carbides in solution, and this decreases the magnetic permeability of the steel. This lessened permeability is probably due to some asymmetry of the iron atoms, making it more difficult for the magnetons to align themselves in the direction of the magnetic field. This would be expected

[4] See A. P. Chattock, Phil. Mag., **24**, 94, 1887

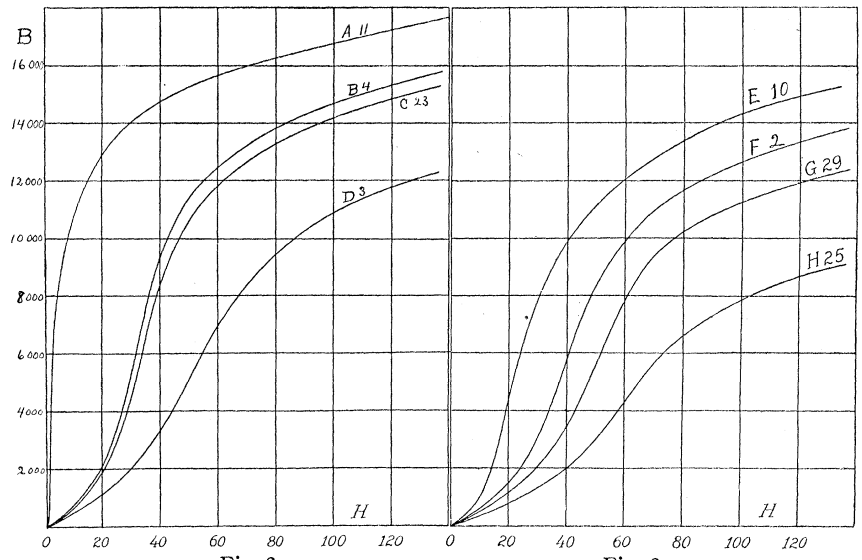

Fig. 2

Fig. 3

Fig. 2. Hardened carbon steels, showing the normal magnetization curves with different percentages of carbon.

Fig. 3. Hardened chrome steels. Showing the normal magnetization curves with different percentages of carbon.

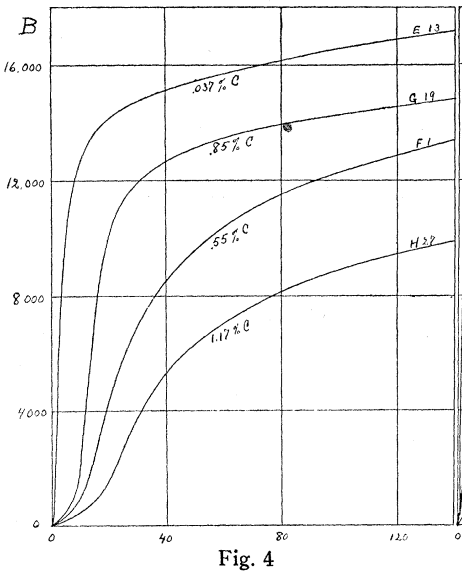

Fig. 4

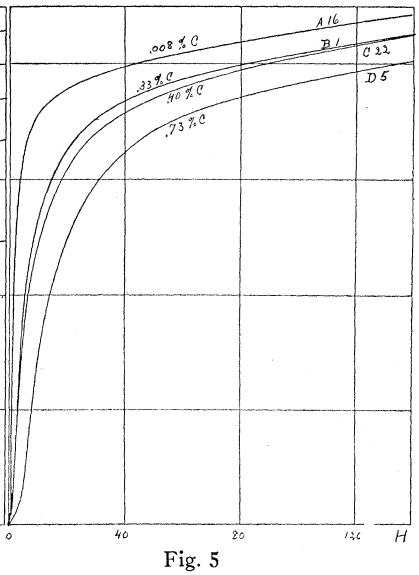

Fig. 5

Fig. 4. Normal magnetization curves for the annealed bars of chrome steel, with varying carbon content.

Fig. 5. Normal magnetization curves for the annealed bars of Armco iron with varying amounts of carbon added.

to require a greater value of the applied magnetic field to produce a given degree of magnetization. The maximum value of the permeability, or the minimum value of the reluctivity, for a given steel is attained under the conditions in which the magnetons within the atoms of iron are most free to add their magnetic effect to that of the applied field. The curves marked H in Figs. 6 and 7 show the relation between the percentage of total carbon and the values of H that will bring the corresponding steel to this condition of maximum permeability. For the hardened chrome steels this relation is linear, and it is nearly so for the carbon steels. The curves marked R show the corresponding relation between the minimum value of the reluctivity and the percentage of carbon. These curves are linear except for the last point in Fig. 7.

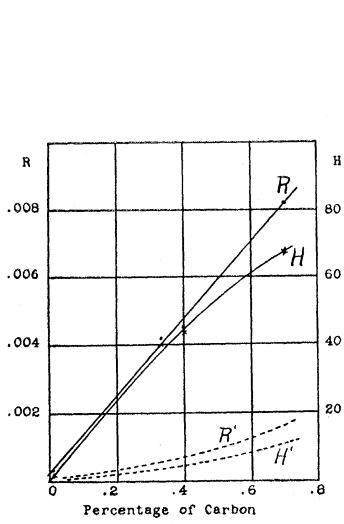

Fig. 6

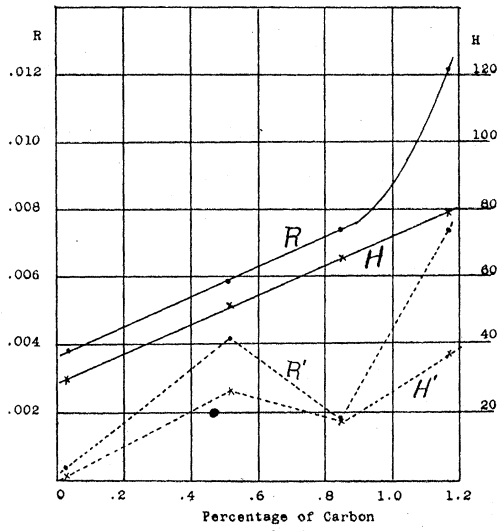

Fig. 7

Fig. 6. Hardened carbon steels. Curve R shows the minimum values of the reluctivity for varying carbon content. Curve H shows the values of H necessary to bring the steels to the point of maximum permeability. Curves R′ and H′ show the corresponding values after the steels have been annealed.

Fig. 7. Hardened chrome steels. Curve R shows the minimum values of the reluctivity of the different steels for varying carbon content. Curve H shows the values of H necessary to bring the steels to the point of maximum permeability. Curves R′ and H′ show the corresponding values after the steels have been annealed. Note the drop in these curves at .8 per cent carbon.

Prof. J. A. Ewing has recently suggested[5] a model for the iron atom in which an inner group of electrons may act as an elementary magneton. In pure iron this magneton can turn easily and align itself with the

[5] J. A. Ewing, Proc. Roy. Soc. Edin. **42**, pp. 97-128, 1922

magnetic field, but in alloys, solid solutions, or compounds, the atom is under non-symmetrical forces and the magnetons are less free to follow the external field.

In the annealed bars the carbides have had ample opportunity to separate out of the solid solution, and therefore the effect of the carbon is much less. This is shown by the corresponding curves (dotted lines) at the bottom of each figure. In the case of chrome steel a very striking effect appears for .85 per cent of carbon. This steel behaves like a steel of much smaller carbon content, having a maximum permeability over twice as large as the steel with .52 per cent carbon. This effect does not appear in the straight carbon steels, and is due to a combination of the chromium and carbon that in effect removes some of each of these elements from the iron. Beyond this point, with the chromium largely combined with the carbon, the excess of carbon produces its normal effect of increasing the reluctivity of the steel.

PHYSICS LABORATORY
UNIVERSITY OF MICHIGAN,
September 18, 1923.