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THE MAGNETIZATION OF IRON IN THE ABSENCE OF HYSTERESIS.

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ANY investigation of the magnetic properties of ferro-magnetic substances is complicated by the presence of hysteresis. Even the curve, usually known as the magnetization curve, is, as Steinmetz[1] points out, but one side of an unsymmetrical hysteresis loop, and differs from any other loop only in passing through the origin. The advantages to be gained in suppressing hysteresis are evident. Without hysteresis, the magnetization becomes a single-valued function of the magnetizing field and it is feasible to attempt an equation connecting them. Again, the true effect of the temperature upon magnetization may be investigated, for the effect of temperature upon hysteresis is so marked that its true effect upon magnetization may be entirely masked, especially in the case of weak fields.

In general, two methods have been proposed for suppressing hysteresis, mechanical shocks or vibrations and an alternating magnetic field, either transverse or longitudinal. Ewing[2] employed mechanical vibrations while Finzi,[3] Ashworth,[4] and Steinhaus and Gumlich[5] used alternating fields superposed upon the magnetizing field. Ashworth alone investigated the change of magnetization with the temperature, but his results, while free from hysteresis, were distorted by the alternating field which was present in the specimen. Steinhaus and Gumlich avoided this distortion by reducing the alternating field to zero before observing the magnetization produced in the specimen due to the applied magnetizing field.

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[1] Steinmetz, Theory and Calculation of Electric Circuits, p. 50.

[2] Ewing, Phil. Trans., p. 564, 1885.

[3] Finzi, Electrician, 26, 672, 1891.

[4] Ashworth, Phil. Mag., 27, 357, 1914.

[5] Steinhaus and Gumlich, Ber. d. Deut. Phys. Ges., 17, 369, 1915.

The present work is, in a sense, a repetition of Ashworth's work on iron, using the method of Steinhaus and Gumlich. Five specimens were prepared from samples furnished through the kindness of Professor E. D. Campbell. These included three hypo-eutectoid steels, a very pure basic open-hearth steel, and an ingot iron. Their composition was furnished with them and appears in Table I. These five form a series of steels with decreasing carbon content whose last member approximates pure iron. The specimens were made in the form of ellipsoids of revolution, 20 cm. long and 0.47 cm. in diameter.

TABLE I.

Composition of Steels in Per Cent.

Steel.	C.	Mn.	P.	Si.	Cu.	S.
H57	0.57	0.11	0.010	0.17		0.020
H41	0.41	0.08	0.012	0.19		0.016
H35	0.35	0.08	0.009	0.18		0.024
04	0.04	0.10	0.007			0.029
INI	0.015	0.016	0.005		0.045	0.03

APPARATUS.

A magnetometer was used for observing the magnetization of the specimen. Two identically wound solenoids were mounted east and west with the principal needle of the magnetometer on their common axis and between them. These solenoids were made of brass tubes, 4 cm. in diameter, with a layer, 60 cm. long, of No. 20 enamelled copper wire wound on them. They made available magnetizing fields up to 100 gauss in strength. The one solenoid, which was used for magnetizing the specimen, had a second layer wound on it, by which the required alternating field could be produced. Each solenoid was mounted in a copper tank which was water cooled. The second solenoid was used to balance the first and could be shifted longitudinally.

The magnetometer was of the astatic type devised by Kohlrausch and Holborn.[1] The moving system consisted of two sets of two needles each, 2.0 cm. long and 0.09 cm. in diameter, mounted at the ends of a glass rod, 70 cm. long and 0.1 cm. in diameter, and was suspended by a quartz fiber, 40 cm. long and 30 microns in diameter. Though the upper needles were slightly stronger, the instrument possessed a steady zero point and was sufficiently sensitive, a field of 0.00005 gauss causing a scale deflection of 2 mm. with a scale distance of 1.5 m. As the magnetometer was to be used in a null method, these were the only require-

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[1] Kohlrausch and Holborn, Ann. d. Phys., 10, 287, 1903.

ments to be met and it was not necessary to ascertain to what extent the needle systems differed.

The magnetization produced in the specimen was measured by means of a coil, mounted on the side of the magnetometer opposite to the specimen and at an equal distance. By passing a suitable current through this coil, the deflection produced by the magnetization of the specimen was balanced and the needles of the magnetometer were brought back to their zero position, which was indicated by the familiar lamp, slit, mirror, and scale device. The magnetization of the specimen could then be calculated in terms of the current and the constants of the coil and the ellipsoid. The coil was made by winding No. 20 enamelled copper wire upon a core of Keene cement, a disc 17.3 cm. in diameter and 3.1 cm. thick. A slot was cut on the rim of the disc and a single layer of wire wound on it. This layer was covered with more cement and a new surface was cut after the cement had hardened. On this new surface, a second layer was wound and the process was repeated until five layers had been put on, separated from each other by from two to four millimeters of cement. This method of assembling the coil permitted the accurate measurement of the dimensions of each layer and the field of the coil could be calculated from the formula for a single layer.

The data taken for a given magnetization curve involved the determination of the corresponding values of two currents, that through the magnetizing solenoid and that through the coil. This method for determining the magnetization seems to have much in its favor. It is independent of changes in the sensitivity of the indicating instrument and in the strength of the earth's field, even if the magnet systems are not exactly equal and are not accurately placed in the magnetic meridian. It replaces readings of a telescope and scale with those of a second ammeter, one having to be read for the magnetizing current, and thus affords two observations of the same type. It would seem that there is no difference in the rapidity with which observations can be taken since this depends so largely on the period and damping of the magnetometer in any method.

A 60-cycle alternating current, regulated by means of a water rheostat, was used in the outer winding of the magnetizing solenoid to produce the requisite alternating field. This rheostat had two electrodes of copper whose area was about 150 cm.^{2} and, by lifting the movable electrode, the current could be reduced from about ten amperes to a few hundredths of an ampere before the final break occurred. It may be questioned whether such a device for reducing the current is legitimate, since it does involve a break in the current, though not until the latter is small. By this means, however, the same magnetization was produced in the specimen for a given field, though the initial state was varied as widely as possible, and this should be a conclusive test for the absence of hysteresis. An objection to the rheostat may also be based upon its rectifying action due to inequality in the areas of the electrodes as the movable one is removed from the water. It was found, however, that the magnetization did not depend upon the direction of the rectified current through the solenoid. Evidently, when the alternating current became small enough to be neglected, the rectified portion was also neglible.

The specimen was heated by means of an electrical heater which fitted snugly within the brass tube of the magnetizing solenoid. The heating wires were of 25 per cent. nickel-steel and ran longitudinally, being held in place by alundum cement at equal spaces around the heating chamber. The latter was 60 cm. long and 1 cm. in diameter. A longitudinal winding produced no magnetic field within the heating space and secured a more uniform temperature throughout that part in which the specimen lay. The necessary thermal insulation was secured by two concentric quartz tubes, separated by asbestos, which slipped over the hollow alundum cylinder in which the wires were set. The heater was slightly magnetic below 500° C. but separate observations were taken to correct for this.

The ends of the magnetizing solenoid were provided with brass cover plates, made oil tight with asbestos gaskets. Through one plate passed a brass plug in which were mounted the tubes for a platinum resistance thermometer. The thermometer wire with its leads was stretched in a quartz tube, 1 mm. in bore, which was then bent double. The wire was long enough to traverse the length of the specimen twice, the latter being supported by the same tube which contained the wire. The compensating leads were mounted in a shorter piece of the same tubing. With such a thermometer the average temperature throughout the specimen was indicated.

EXPERIMENTAL RESULTS.

The usual procedure with a specimen began with heating it for about an hour and a half in the neighborhood of the Curie point in order to anneal the specimen and to secure thermal equilibrium in the heater, solenoid, and oil bath. The temperature was then reduced slowly, step by step, and magnetization curves were taken at suitable intervals. The greatest change in magnetization occurred within the first one hundred degrees below the Curie point and from four to five hours were allowed for this interval. About twice this time was taken for the specimen to cool completely to room temperature. Measurements were taken during cooling that they might be more free from irregularities due to previous thermal and mechanical treatment of the steels.

The magnetization curves obtained for specimen H35, the softest of the hypo-eutectoid steels, appear in Fig. 1. These are typical of the isothermals obtained for all five steels. The abnormally high susceptibility for low magnetizing fields, which seems to be the most pronounced characteristic of anhysteretic curves, persists up to the immediate neighborhood of the transformation point. The curves are uniformly concave to the *H*-axis and do not intersect each other except at the origin, though the curves are not conclusive on this latter point. The true magnetizing field is obtained as the difference between the applied field and the demagnetizing field due to the ellipsoid itself and this results in relatively great uncertainty in the value of *H* when the field is weak. In the case of the softest of the steels, this difference was less than the error in the observations for applied fields as large as ten gauss and intensities of magnetization as high as nine hundred.

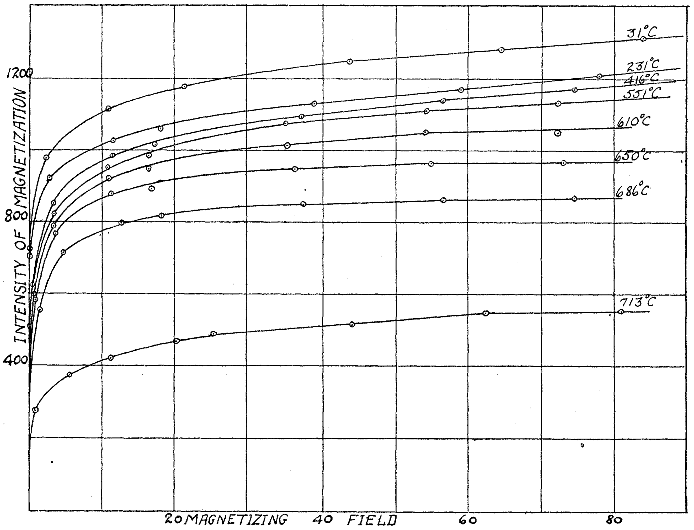

Fig. 1.

If, as seems likely, any given isothermal lies wholly beneath any other which corresponds to a lower temperature than the former, the magnetization for a given field decreases with a rise in the temperature. In the absence of hysteresis we do not find the anomaly common to ordinary magnetization curves, namely, that the magnetization for a given field may either increase or decrease with rise of temperature, depending upon whether the field is weak or strong. In Fig. 2 are found the magnetization curves for all five specimens for a constant field of sixty gauss. It is evident that the curve for specimen *INI*, which is most nearly free from carbon, is by far the most regular. The effect of carbon is to produce two irregularities, the one just above 700° C. and the other in the neighborhood of 200° C. The former corresponds to the precipitation of the carbides which occurs at the eutectoid point. The latter is due to the magnetic transformation of the cementite in the steel. The actual shape of the curves at this lower transformation point is not definitely indicated by the data but must be somewhat as shown by the dotted portions. The transformation point certainly lies between 180° C. and 220° C. which agrees with Honda's[1] work on cementite. For the purpose of the present investigation, a more exact knowledge of the curves in this region was not necessary.

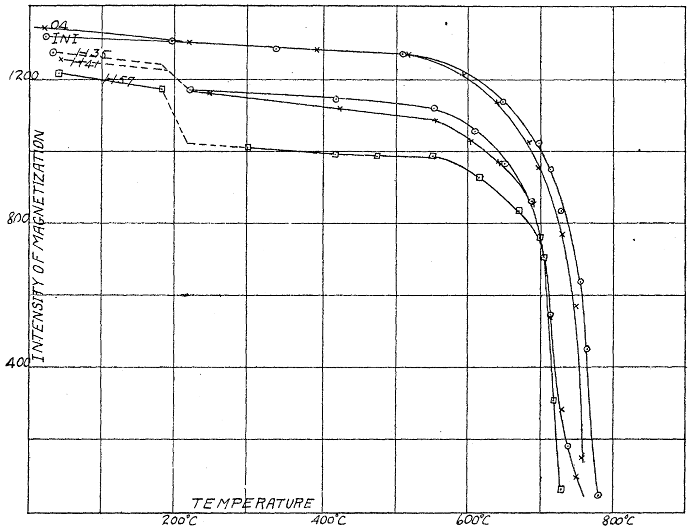

Fig. 2.

Equations for Anhysteretic Curves.

Examination of the curves in Fig. 1 shows them to be smooth and regular, whether they are for iron or steel. The curves have at least three distinguishing characteristics, a uniform concavity to the H-axis, an infinite slope at the origin, and a finite limit to the ordinate as the abscissa increases indefinitely. The curves, of course, furnish no con-

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[1] Honda and Takagi, Journ. Iron and Steel Inst., 92, 181, 1915.

clusive proof of the third characteristic but they indicate nothing contrary to this, the ordinarily accepted view. The appearance of the isothermals suggests the possibility of obtaining an equation for a given curve. But Fig. 2 shows clearly that to introduce the temperature as a variable in the equations will be feasible only in the case of carbon-free iron.

The only equation yet proposed for anhysteretic isothermals is empirical and due to Fröhlich. Finzi and Ashworth (loc. cit.) have both attempted to apply this equation to their experimental results. Steinmetz[1] has shown that the same equation may be fitted to limited ranges of the ordinary magnetization curve and expresses his opinion that it should probably fit an anhysteretic curve throughout its whole extent. The equation is based upon the assumption that the susceptibility is proportional to the amount by which the magnetization may yet be increased. Expressed in symbols, this becomes

$$\frac{I}{H} = K(I_0 - I),$$

where I_0 is the maximum intensity of magnetization and K a constant. This may be transformed into the more useful form

$$H\left(\frac{1}{I} - \frac{1}{I_0}\right) = A,$$

where A is a new constant. This equation is hyperbolic in H and I, but is linear in H and H/I. In Fig. 3, the data of Fig. 1 are plotted with this second pair of variables as coördinates and it may be seen to what extent the linear relation holds. Where a straight line fails to fit the points, a continuation, either straight or curved, has been made which will do so, in order that there may be less confusion as to corresponding lines and points. The continuations have been indicated by the dotted lines. In none of the isothermals does the equation seem to hold for fields much less than twenty gauss and, in two, at least, there is an indication that the relation is not linear through the upper range of available fields. This failure of the equation to hold may be considered from another viewpoint. If we form the derivative from the equation, we obtain

$$\frac{dI}{dH} = \frac{1}{A}\left(1 - \frac{I}{I_0}\right)^2.$$

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[1] Steinmetz, Theory and Calculation of Electric Circuits, p. 54.

At the origin, this becomes

$$\left(\frac{dI}{dH}\right)_0 = \frac{1}{A}$$

and the condition for infinite slope can be fulfilled only by making A vanish, which would reduce the hyperbola to two straight lines.

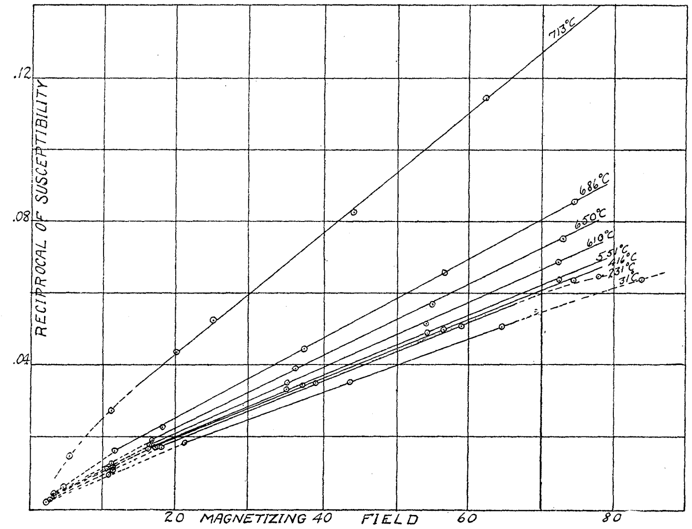

Fig. 3.

The results indicate that Fröhlich's equation does not fit the anhysteretic isothermal magnetization curves, though it may be made to fit a limited range of any curve and may be used as an approximation for the curve. Ashworth[1] not only accepts Fröhlich's equation for a given isothermal but attempts to use it for the whole family by introducing the temperature as a third variable. He does this from analogy with Van der Waal's equation and writes Fröhlich's equation in the form

$$H\left(\frac{1}{I} - \frac{1}{I_0}\right) = RT,$$

where R is a constant and T the absolute temperature. For H constant, this equation is hyperbolic in T and I. But the hyperbola of the equation is convex toward the T-axis whereas the curves of Fig. 3 are concave. This difficulty might be met by assuming that I_0 is a function of the temperature but, since it is an unknown function, it does not seem that Ashworth's equation is a step in advance of that of Fröhlich.

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[1] Ashworth, loc. cit.; also Phil. Mag., 33, 349, 1917.

Summary.

1. A null method for using the magnetometer has been described.
2. From a series of steels with decreasing carbon content, the anhysteretic magnetization curves for iron have been approximated and certain characteristics of these curves have been pointed out.
3. It has been shown that the equation proposed by Fröhlich does not fit the anhysteretic isothermal magnetization curves and that the equation, even when modified as Ashworth proposes, does not give the magnetization properly related to the temperature.

In conclusion, the writer wishes to acknowledge his indebtedness to the late Professor K. E. Guthe, at whose suggestion the work was undertaken, and to the members of the department of physics of the University of Michigan.

University of Michigan,
May, 1917.