THE KOEPSEL PERMEAMETER

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CONTENTS

1. HISTORICAL

The moving coil galvanometer and many other electrical instruments built on the same principle consist essentially of a coil of wire suspended in a magnetic field. This coil experiences a torque which is proportional to the product of the current in the coil and the component of the magnetic field in the plane of the coils. In the instruments just mentioned the magnetic field is constant and the current varies. The deflection due to the torque thus becomes a measure of the current strength.

Instead of using a constant magnetic field, we may maintain a constant electric current through the moving coil and use this system for the measurement of the magnetic field. If this magnetic field is due to an electromagnet, the magnitude of the field depends upon the magnetomotive force applied and the material of the magnetic circuit. An electromagnetic system of this kind may therefore be made the basis of an apparatus for the determination of the magnetic properties of iron and steel.

Robinson [1] in the Electrical World of February 24, 1894, gave a complete description of a permeameter based on this principle. However, he had not actually built the instrument.

Three days later Koepsel [2] described before a German electrotechnical society substantially the same piece of apparatus, which he had built and was actually using. This apparatus, as later improved by Kath,[3] is widely used, both in this country and abroad. It is sometimes called the Siemens and Halske permeameter, from the name of the manufacturer.

Orlich [4] at the Reichsanstalt determined a number of hysteresis loops with the Koepsel instrument and also by the magnetometer method, using ellipsoidal specimens for this latter test. His data show that at inductions of 15 000 gausses the instrument gives values of the magnetizing force which are too high. All values of the coercive force, as obtained by this instrument, are greater than those of the magnetometer. The shearing curves differ for different materials. Rohr [5] compares hysteresis data obtained by the Koepsel permeameter with that obtained by the wattmeter method and finds that the values of the Steinmetz coefficient thus obtained are in substantial agreement. The Koepsel apparatus has also been used by Voller,[6] Gans and Goldschmidt,[7] Aliamet and Brunswick,[8] and others.

Much of the data on the magnetic properties of iron and steel have been determined with this apparatus. It seems, therefore, well worth while to give the Koepsel permeameter a careful experimental examination with a view to determining its reliability for use in making magnetic measurements.

2. THE KOEPSEL PERMEAMETER

Fig. 1 shows the Koepsel apparatus diagrammatically. The magnetic circuit consists of a semicircular yoke J J with its ends

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[1] L. T. Robinson: "A modified instrument for the determination of B-H curves," Electrical World, **23**, p. 236; Feb. 24, 1894.

[2] A. Koepsel: Apparat zur Bestimmung der magnetischen Eigenschaften des Eisens in absoluten Maas und directer Ablesung, E T Z., **15**, p. 214; Apr. 12, 1894.

[3] H. Kath: E T Z., **19**, pp. 411–415; 1898.

[4] E. Orlich: E T Z., **19**, pp. 291–294; 1898.

[5] W. Rohr: E T Z., **19**, p. 713; 1898.

[6] A. Voller: Hamburg Verh. Natw. Ver. (3 folge), p. 8; 1900.

[7] Gans and Goldschmidt: E T Z., **17**, pp. 372–374; 1896.

[8] Aliamet and Brunswick: Électricien, **16**, pp. 187–191; 1898.

joined by the test piece P. The middle of the yoke has a circular gap in which swings the test coil *h* for the measurement of the induction. The system is magnetized by means of a current in a solenoid S, surrounding the specimen. The constants of the

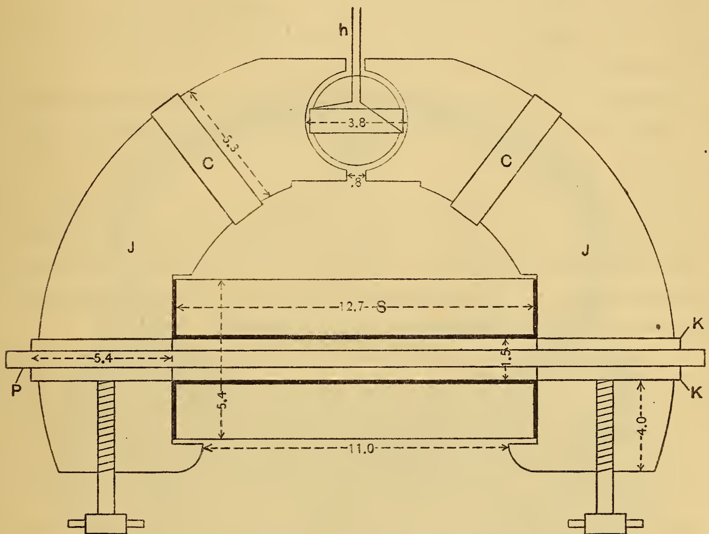

FIG. 1.—*Diagram of the Koepsel permeameter*

P Test specimen
JJ Heavy semicircular soft iron yokes
K Soft iron bushings
S Main Magnetizing solenoid
CC Compensating turns
h Moving coil
(The dimensions given on the figure are in centimeters.)

instrument are such that the magnetizing force is given by the equation

$$H = 100\ I$$

where I is the magnetizing current in amperes, and H is the magnetizing force in gausses.

This coil is designed for values of H as large as 450 gausses, so that it must have a carrying capacity of 4.5 amperes. In order to eliminate, when there is no specimen in the apparatus, any deflection of the moving coil due to the magnetizing effect which the main solenoid exerts on the yokes, compensating turns C C are wound about the yokes near the test coil and connected in series with the main solenoid, but in such a direction that they oppose the main magnetomotive force. The effective value of the current in the compensating turns is adjusted by shunting until there is no deflection of the coil when the maximum current is flowing but with no test specimen in place.

Through the coil *h* is maintained a current of such a value that the deflection due to the reaction between the coil and the field, as read on the uniform scale, is numerically equal to the flux density in the specimen.

This current is inversely proportional to the cross section of the specimen and is equal to a constant divided by the cross section.

All the newer apparatus is adjusted by the maker until this constant is 0.005. The standard rod 0.6 cm in diameter therefore requires an auxiliary current of 0.2827 ampere.

In the use of the instrument it is necessary to observe several precautions. The instrument should be so oriented that the axis of the moving coil is in the plane of the magnetic meridian; otherwise, there will be a small torque due to the magnetic field of the earth. Masses of iron, particularly if magnetized as in the case of many electrical instruments, should be removed from the immediate neighborhood of the apparatus. The specimen should be of such length that it will not project any considerable distance beyond the yokes. Projecting ends may modify the field in the place occupied by the moving coil. Care should be taken that the glass cover does not collect a charge of static electricity. Such charges may exert a force on the light aluminium pointer sufficient to introduce an error in the induction. After inserting the test specimen in the apparatus it should be thoroughly demagnetized. Residual induction in the bar or yokes will cause a deflection of the instrument even when no magnetizing current is flowing. It is very difficult to reduce this residual deflection to zero, but it should be made quite small, not over a few hundred gausses. To eliminate the errors due to residual induction in the yokes, to a displacement of the zero point, or to the earth's field (since this has an effective component when the coil is in the

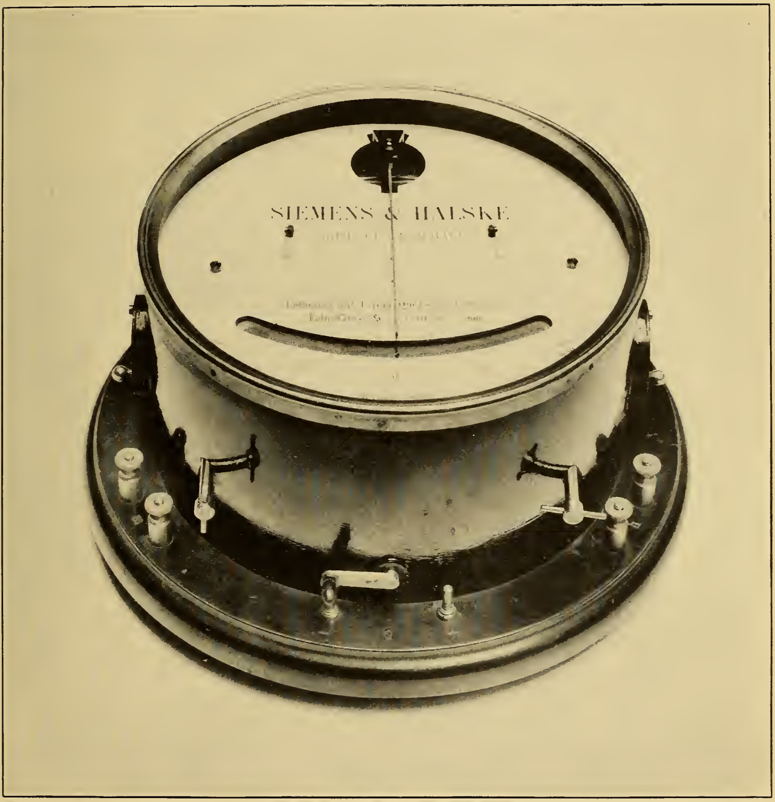

FIG. 2.—*Photograph of the Koepsel permeameter used in this investigation*

deflected position) it is necessary to take readings on both sides of the zero point. This may be done by reversing either the auxiliary or the magnetizing current, preferably the latter, since in that method partial correction is made for errors due to the imperfect demagnetization of the test piece.

In the present investigation the normal induction data were obtained by reading the magnetic inductions with the magnetizing current first in one direction and then in the reverse direction. The mean of these two readings gives more consistent results than the method, given in the maker's instructions, of varying the magnetizing current step by step without reversals. In determining the hysteresis data, however, the step-by-step method was followed.

3. CONSISTENCY ON REPETITION

The first requirement of a permeameter is that it shall give the same readings on different determinations of the same material. Table 1 shows two sets of data taken in succession and without removing the test material from the apparatus.

TABLE 1

Typical Koepsel Data

BAR NO. 293, 0.6 CM DIAMETER

H	First set			Second set			ΔB_{mean}
	B+	B−	B_{mean}	B+	B−	B_{mean}	
1	650	25	337	600	100	350	13
2	1700	1100	1400	1650	1150	1400	00
3	3500	2950	3225	3450	3000	3225	00
4	5100	4800	4950	5100	4850	4975	25
6	8000	7900	7950	8000	7975	7987	37
8	10 050	10 000	10 025	10 250	10 000	10 125	100
10	11 500	11 400	11 450	11 500	11 400	11 450	00
20	14 600	14 500	14 550	14 700	14 300	14 500	50
50	16 800	16 400	16 600	16 700	16 450	16 575	25
100	17 950	17 500	17 725	17 900	17 650	17 775	50
300	20 000	19 500	19 750	19 900	19 600	19 750	00
						Mean..	27

B and *H* are expressed in gausses. *B*+ and *B*− correspond to the two directions of the corresponding magnetizing force.

The two readings $B+$ and $B-$ on the two sides of the zero for the same magnetizing force differ widely from each other, especially in the initial inductions. These differences are probably due to a residual induction of the yokes, although very great care was used in demagnetizing. This failure to get complete demagnetization of the yokes is due to the fact that in some earlier use of the apparatus with test rods of larger diameter the yokes were carried to a higher flux density than can be reached with the smaller rods. Other experiments have shown that a closer equality between the two readings is obtained when care has been taken to demagnetize the yokes with a large rod in place before the smaller one to be tested is inserted.

The individual readings in the two sets of data given above differ quite appreciably, but the mean values of each set differ only slightly. Experiment shows that if more careful demagnetization of the yokes had been carried out, as indicated above, the resulting mean values would have been in substantial agreement with those here obtained. The differences noted in the last column of Table 1 may all be accounted for as errors of observation. The smallest graduation on the scale is about 2.5 mm long and represents an induction of 500. The maximum difference in the table of 100 gausses represents an error of one-fifth of a division and may be distributed over four readings. The mean difference of 27 corresponds to an error in estimation of 1/18 division. We may conclude, therefore, that this apparatus yields results which are reproducible.

4. SHEARING CURVES

To test the accuracy of the data obtained by the Koepsel apparatus a number of rods were measured by this apparatus, and also by the author's compensated double-yoke method.[9] Fig. 3 may be taken as representing the results of such a comparison. The Koepsel apparatus indicates a magnetizing force which is too high for the lower inductions. This error in magnetizing force increases as the induction increases up to a certain stage, when it decreases, passes through zero, and reaches a maximum of opposite sign. Finally it approaches the zero value again and in some cases even changes sign a second time.

[9] Burrows: "The determination of magnetic induction in straight bars." This Bulletin, 6, pp. 31–88; 1909 (Reprint No. 117).

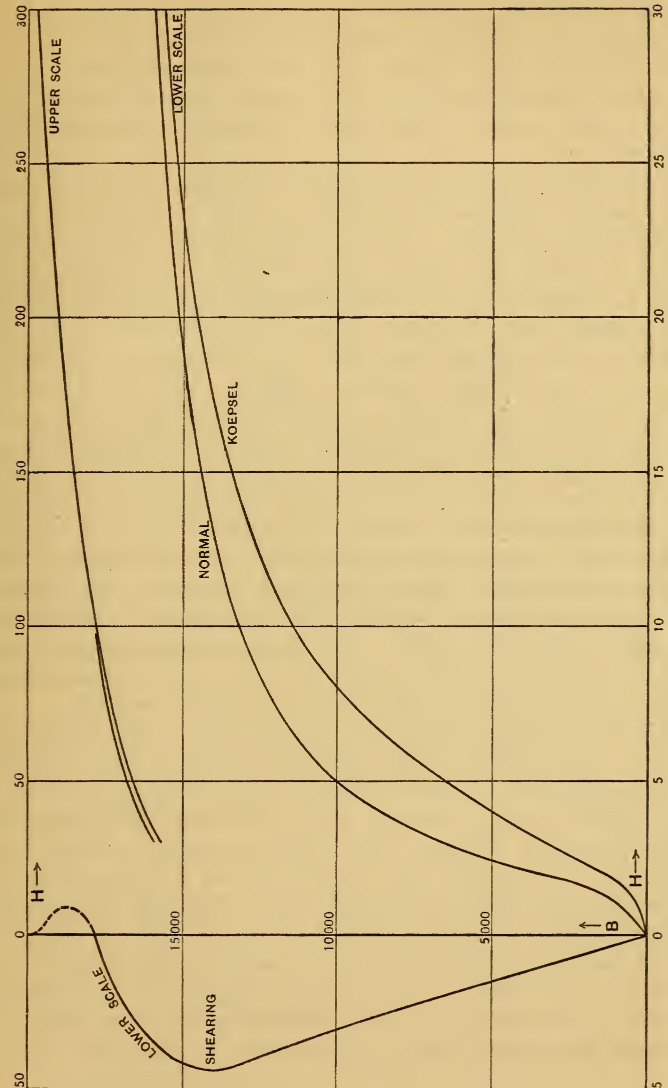

FIG. 3.—*Showing the normal induction and shearing curves of a wrought iron rod 0.6 cm in diameter as measured by a Koepsel permeameter*

These variations are well shown in the curve of corrections or "shearing curve," as it is usually called. The true points on the induction curve are obtained from the observed values by a shearing parallel to the H axis by an amount equal to the abscissa of the point on the shearing curve having the corresponding induction.

If the shearing curve is constant for specimens of different size and quality, the apparatus would be perfectly reliable for permeability measurements. Unfortunately, however, this correction is not a constant nor does it vary according to any simple law. Figs. 4, 5, and 6 show the normal induction and shearing curves for wrought iron, low-carbon steel, and high-carbon steel, as obtained on the Koepsel apparatus. For comparison, the shearing curves are brought together in Fig. 6. This set of curves shows a number of interesting things. At an induction of 5000 gausses the correction to be applied to the observed magnetizing force is negative and increases in magnitude as we pass from wrought iron to low-carbon steel and to high-carbon steel; that is, the shearing correction is greater for the harder material. At an induction of 15 000 gausses each correction curve has crossed both of the others and the order is completely reversed. The curves show zero correction at inductions which increase as we pass from the hard to the soft material. The maximum positive correction and the maximum negative correction occur at inductions which are lower for the hard material than for the softer material.

It is obvious that the correction does not depend on the induction alone. For accurate use the apparatus should be accompanied by shearing curves of material similar to that under examination. The result of using a shearing curve determined from material which is slightly different from the test material is shown in Table 2. The shearing curve used is that of a low-carbon steel while the test material is wrought iron. The full normal and shearing curves of these two rods are shown in Fig. 6. Table 2 shows that the use of the low-carbon shearing curve results in an error of 10 per cent or over in magnetizing force. If shearing curves of substantially the same material as the test specimen are used, data correct within 5 per cent may be expected.

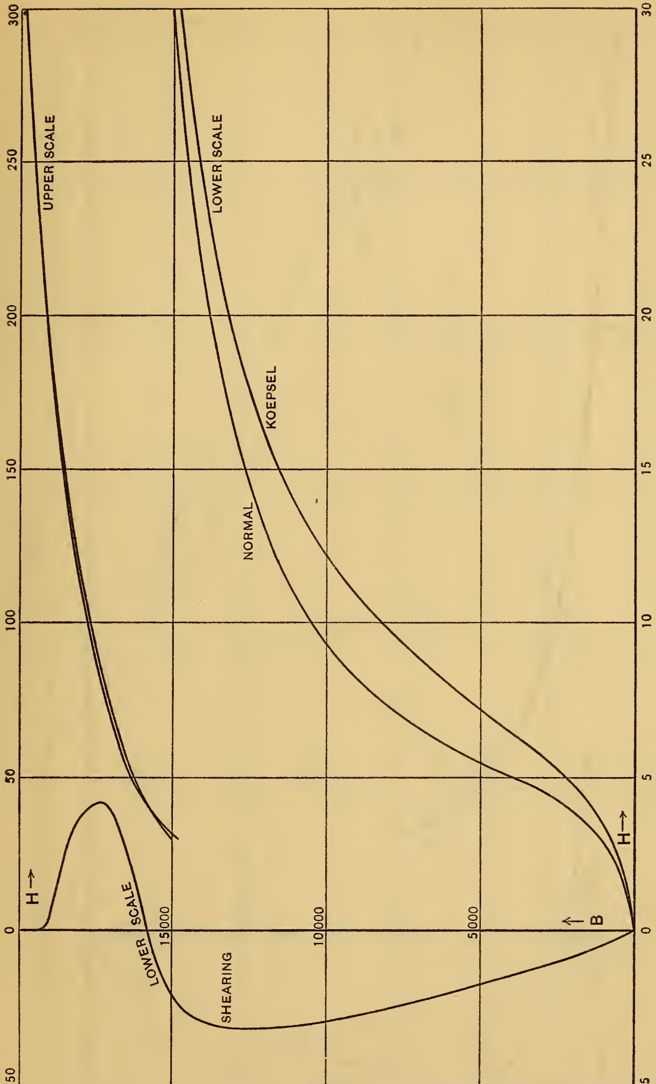

FIG. 4.—*Showing the normal induction and shearing curves of a low-carbon steel rod 0.6 cm in diameter as measured by a Koepsel permeameter*

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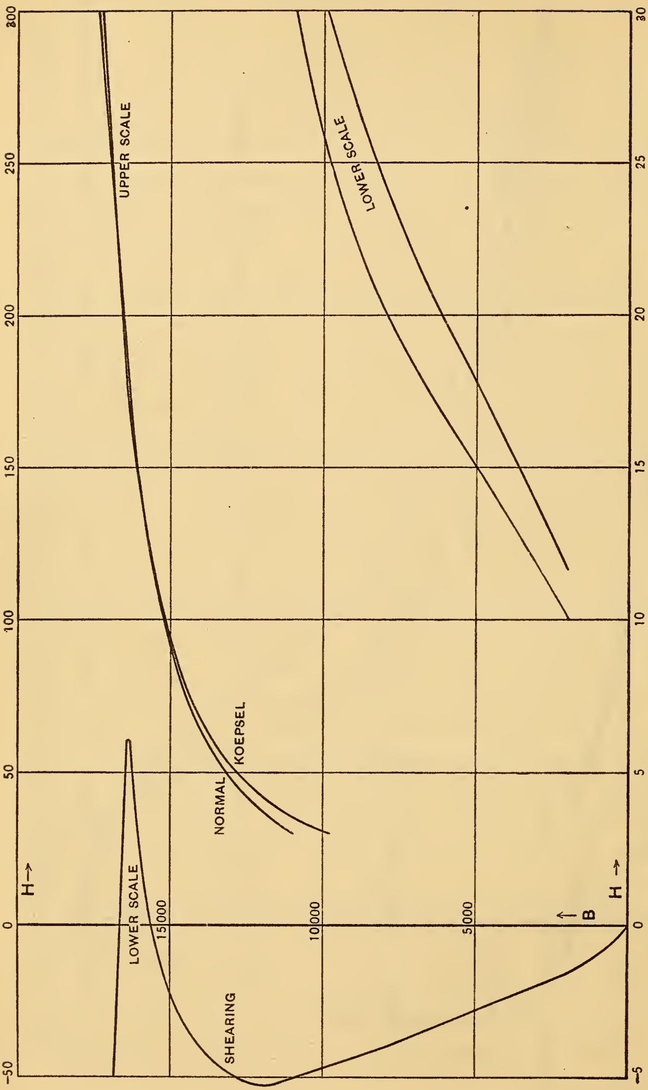

FIG. 5.—*Showing the normal induction and shearing curves of a high-carbon steel rod 0.6 cm in diameter as measured by a Koepsel permeameter*

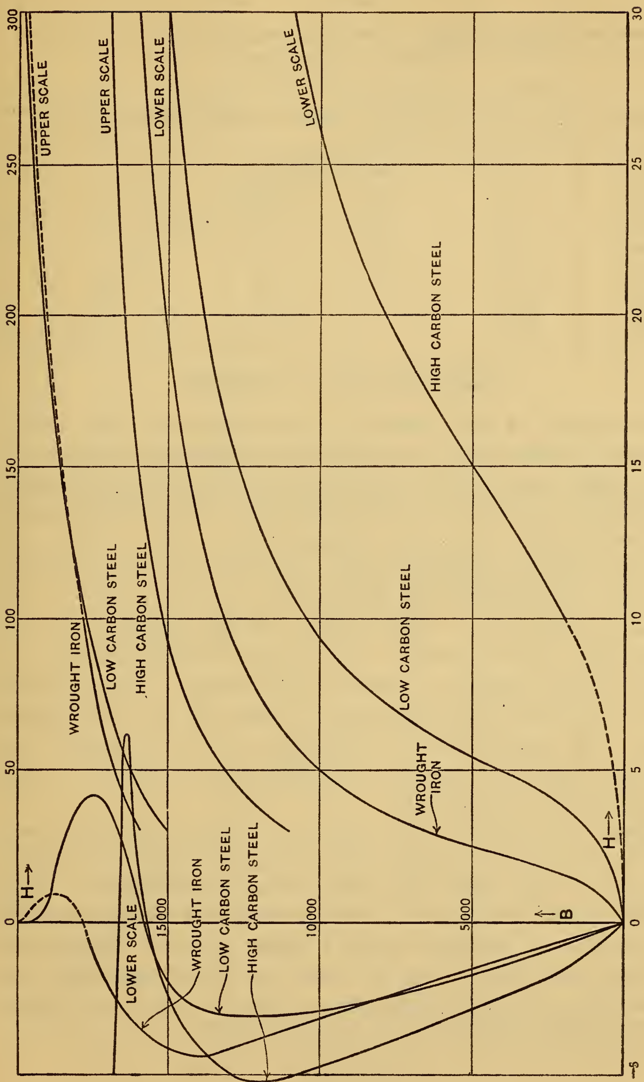

FIG. 6.—*Showing normal data and the variation of the Koepsel shearing curve with different materials*

TABLE 2

Showing the Results of Using a Low-Carbon Steel Shearing Curve with Data Obtained on Wrought Iron

B gausses	H true gausses	H (wrought iron) −H (steel)	Shearing applied	Error in H	Percent error in H
2 000	1.60	− 2.30	−0.78	−0.16	−10
4 000	2.20	− 2.85	−1.45	−0.25	−11
6 000	2.84	− 3.15	−2.02	−0.20	− 9
8 000	3.68	− 3.65	−2.50	−0.04	− 1
10 000	4.98	− 4.35	−2.90	+ .26	+ 5
12 000	7.35	− 5.65	−3.10	+ .76	+12
14 000	12.95	− 7.9	−2.86	+1.50	+12
16 000	30.00	−15.1	+1.00	+4.45	+15
18 000	115.00	.0	+3.70	+3.2	+ 3

5. CROSS SECTION OF SPECIMEN

The influence of cross section was determined by using narrow strips and building them up into bundles of different cross sections. These strips were cut from the same material and a preliminary examination was made to make certain that the individual strips were substantially equivalent magnetically. Fig. 7 shows the curves for strips of transformer steel (silicon steel) 0.037 cm thick. This material was tested in bundles of 4, 8, and 16 strips. The curves all intersect at approximately 10 000 gausses. For all points below this intersection the apparent magnetizing force is greater for the bundles of greater cross section. For all points above this intersection the reverse is true and in more marked degree. For instance, at an induction of 16 000 gausses the observed magnetizing forces for the 16, 8, and 4 strips are 52, 95, and 285 gausses, respectively.

Similar experiments were performed on a low-carbon steel, using, in this case, rectangular rods 0.39 by 0.63 cm in cross section. The curves in Fig. 8 show the same general characteristics. They intersect at an induction of 13 000 gausses, and below this value the two rods in parallel require a larger apparent magnetizing force than one alone. The two rods were tested separately and showed quite appreciable differences. The curve has been plotted from the mean values of the two separate rods.

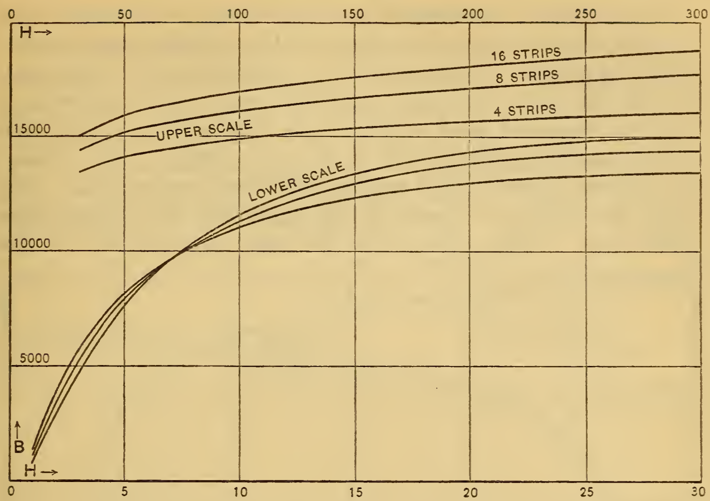

FIG. 7.—*Showing the variation of Koepsel data of transformer steel for differences in cross section*

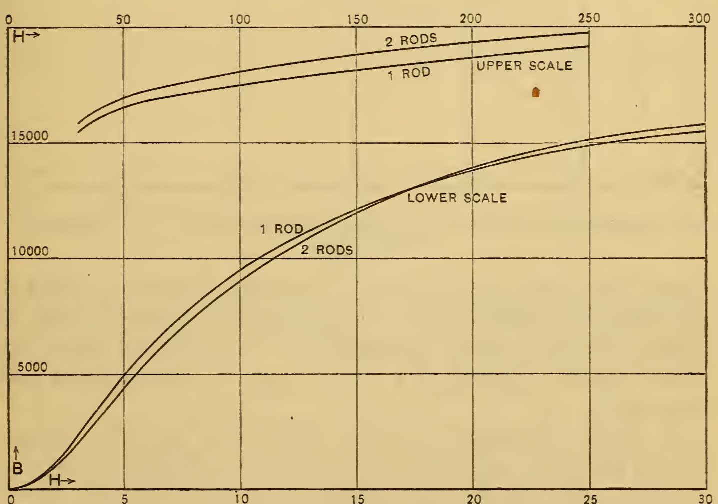

FIG. 8.—*Showing the variation of Koepsel data of low-carbon steel for differences in cross section*

The changes in cross section were quite large in the cases of the wrought iron and low-carbon steel, and the question arises whether small variations in cross section are proportionately important. To test this point and also to get data on a harder material 11 strips of tempered steel tape 0.63 cm wide and 0.047 cm thick were measured in groups of 8, 9, 10, and 11 strips. Fig. 9 shows the extreme curves for the greatest and least cross sections. The other curves are not shown in the figure but lie between those shown here. These curves show the same characteristics in the

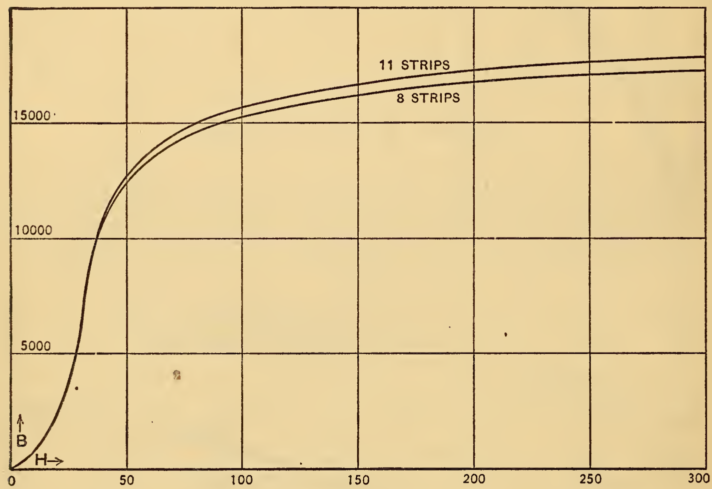

Fig. 9—*Showing the variation of Koepsel data of tempered spring steel for differences in cross section*

upper portions as the preceding. The point of crossing, which is so conspicuous with the softer material and the greater range of cross sections, is barely discernible in the numerical data but would probably develop if a greater range of cross sections had been tried.

From the preceding it is quite evident that separate shearing curves must be supplied, not only for test samples of different materials, but also for test samples of the same material which have widely different cross sections.

6. LENGTH OF SPECIMEN

It seemed quite probable that the length of the specimen might have some influence on the reading of the instrument. With a view of determining the magnitude of any such influence the following experiment was made. A rod 123 cm long was inserted in the Koepsel apparatus with equal lengths projecting beyond each yoke, and measurements taken. The rod was then removed and 10 cm cut off from each end. Magnetic measure-

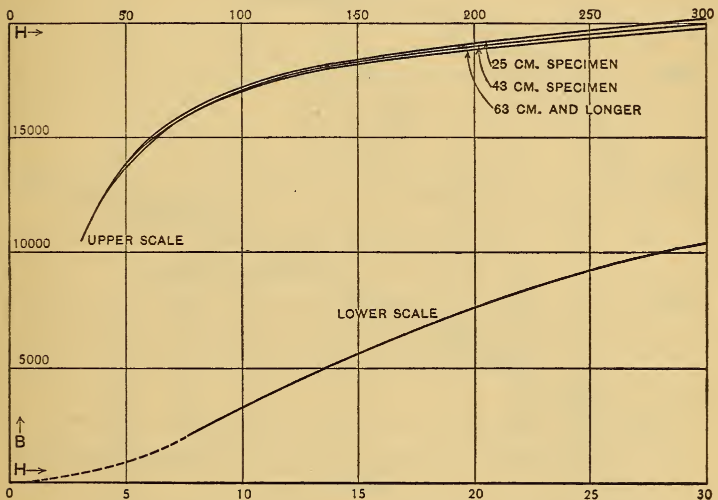

FIG. 10.—*Showing the effect of using specimens whose ends project beyond the yokes of the Koepsel apparatus*

ments were taken as before, taking care that the same portion of the rod was within the apparatus. This operation was repeated until the rod had been reduced to the minimum length that could be used in the apparatus. No change in the readings was noticed until the length of the specimen was reduced below 63 cm.

Fig. 10 shows the curves for lengths of 25, 43, and 63 cm. No variation is noticed in points below the knee of the curve. At higher inductions the curves diverge more and more as the induction increases. The shorter specimens require a lower magnetizing force. The difference is so slight that projections of several centimeters are not serious.

7. POSITION OF BUSHINGS

A more serious source of error is in the proper placing of the bushings. In one run the bushings were inadvertently left pro-

FIG. 11.—*Showing the effect of improper placing of the bushings in the Koepsel apparatus*

jecting beyond the yokes on the outer side by about 5 mm. This has the effect of increasing the effective length of the portion of the specimen tested. Fig. 11 shows the two curves obtained with the bushings misplaced as indicated and with the bushings flush with the yokes as they should be. The differences indicate that some care should be exercised in inserting the test specimen in the apparatus.

8. FLUX DISTRIBUTION IN THE KOEPSEL APPARATUS

The preceding experimental results show that the correction to be applied to the readings with the Koepsel permeameter, to reduce them to true values, depends upon several factors. It has been shown that the magnitude of this correction depends upon the material, length, and cross section of the specimen under test, and also the magnetic condition of the yokes and the position of the bushings.

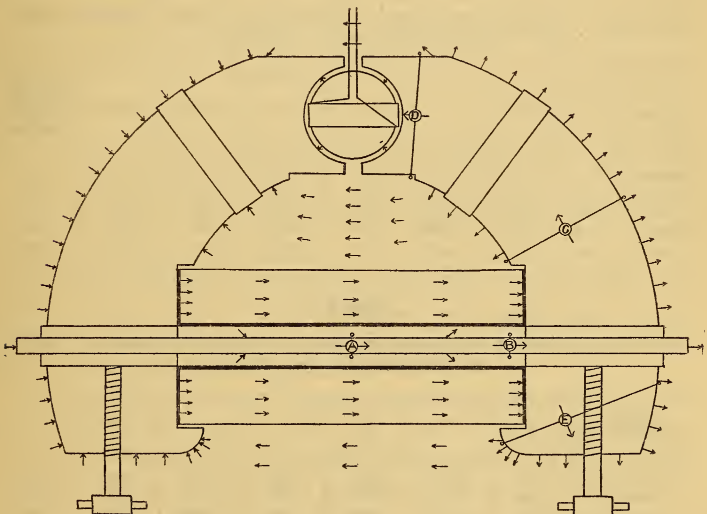

FIG. 12.—*Showing the location of the exploring coils used in the determination of the flux distribution, and the approximate direction of the magnetic flux*

In order to determine more fully the nature of the influence which each of the conditions exerts on the resultant observed values of magnetizing force and magnetic induction, it seems desirable to determine the flux distribution along different parts of the magnetic circuit.

We know that in a general way the magnetic flux in an apparatus of this type is distributed somewhat as shown by the arrows of Fig. 12.

To secure quantative results on the flux distribution, exploring coils of 10 turns each were wound around different cross sections of the magnetic circuit. These were placed over the portions indicated in Fig. 12, by the letters A, B, C, D, and E. Full magnetization curves were taken both with and without current in the compensation coils. A condensed view of the results is given in Tables 3 and 4, where the various fluxes are expressed in terms of the flux through the coil surrounding the center of the test

TABLE 3

Showing the Relative Distribution of the Flux in the Koepsel Apparatus with Normal Compensation. (See Fig. 12)

Current	A	B	C	D	E	C+E	A−B	Decrease in A, due to compensation
Amperes								
0.15	1.00	0.93	0.86	0.76	0.07	0.93	0.07	0.03
0.30	1.00	0.93	0.87	0.78	0.06	0.93	0.07	0.01
0.60	1.00	0.93	0.88	0.79	0.06	0.94	0.07	0.01
3.00	1.00	0.95	0.94	0.79	0.11	1.05	0.05	0.00

TABLE 4

Showing the Relative Distribution of Flux in the Koepsel Apparatus Without the Compensation. (See Fig. 12)

Current (amperes)	A	B	C	D	E	A−B	C+E
0.15	1.00	0.93	0.88	0.79	0.06	0.07	0.94
0.30	1.00	0.93	0.90	0.81	0.05	0.07	0.95
0.60	1.00	0.95	0.92	0.83	0.05	0.07	0.97
2.00	1.00	0.95	1.00	0.91	0.05	0.05	1.05
3.00	1.00	0.95	1.05	0.95	0.05	0.05	1.10

rod. The test rod itself is a low-carbon steel rod of rectangular section 0.9 cm square. The difference, A–B, represents the magnetic leakage from the bar between the center and either end; that is, between A and B. This leakage is nearly constant, but is slightly lower for the higher inductions. It is practically the same with as without the compensation. This leakage flux gives rise to magnetic poles. Due to these poles there is a magnetic force acting in the space occupied by the middle portion of the test rod. This is a demagnetizing force, which varies with the pole strength or, what is proportional to it, the leakage. We see, therefore, that this self-demagnetizing effect is proportional to the magnetic induction, except for points near saturation, where it is somewhat below proportionality. It is what is left of the much larger self-demagnetizing force that would exist if the ends of the bar were not connected by yokes.

The sum C + E is a measure of the greater portion of the flux that enters the yoke. It does not measure the whole flux which enters the yoke, since only those portions which leave through sections C and E are included. The yoke between these two sections is the seat of some leakage, which has been neglected. This flux C + E is less than the flux through the specimen for the lower inductions, but becomes greater as saturation approaches. This latter condition means that more flux enters the yokes than leaves the bar. The resulting polarity of the yokes is the seat of a positive magnetizing force. It is less with the compensation than without it. The explanation of this extra flux is considered more fully in the next section.

The flux through E is the return flux which passes between the yokes through the air without linking the moving coil. It increases at the higher inductions when the compensation is used, but decreases when it is not used.

Column D is the ratio of the flux through the moving coil to the flux through the center of the test rod. If this ratio and the relative leakage around the poletips are constant, the flux through the test coil may be used as a measure of the flux in the specimen. However, this ratio is not constant. Without compensation, it varies from 79 per cent to 95 per cent of the flux through the test piece. With compensation, the ratio is more nearly constant, showing a flux of from 76 per cent to 79 per cent of the flux through the test piece. The variation of this ratio is, therefore, about 2 per cent of its own mean value.

If the scale is calibrated so that the magnetic induction read is proportional to the deflection of the moving coil, the scale may be so calibrated that the induction readings at any point on the scale are not in error by over 1 per cent. This variation at an induction of 20 000 gausses corresponds to an error in the corresponding magnetizing force of 5 per cent or more.

9. THE DIRECT MAGNETIZATION OF THE YOKES BY THE SOLENOID

The excess of flux in the yokes over that in the bar is due to the magnetizing force which is exerted on the yokes by the magnetizing solenoid. The total mmf acting along the yokes of the magnetic circuit is no inconsiderable portion of the applied mmf.

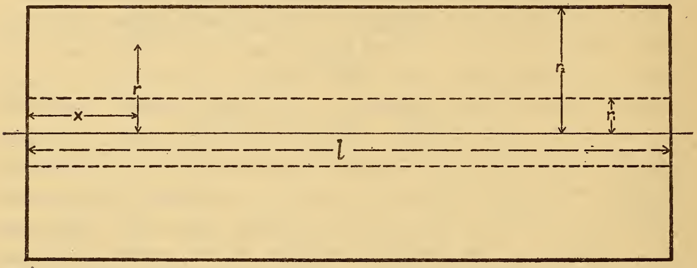

FIG. 13.—*Representing a solenoid of length l whose inner and outer layers have the radii r_1 and r_2 respectively*

If r = radius of any layer

x = distance of a point on the axis from one end of the solenoid

I = current in amperes

n = number of turns per cm

H = magnetizing force in gausses

Then

$$H=\int_{l-x}^{x}\frac{0.2\pi r^2 nI dx}{(r^2+x^2)^{3/2}}$$

$$=0.2\pi nI\left\{\frac{x}{\sqrt{r^2+x^2}}+\frac{l-x}{\sqrt{r^2+(l-x)^2}}\right\}$$

This equation gives the magnetizing force for any point on the axis of the solenoid.

If now we calculate the magnetomotive force along the axis of the solenoid between the planes bounding its ends, we find for the mmf along that portion of the test bar between the yokes:

$$\int_o^l Hdx=\int_o^l 0.2\pi nI\left\{\frac{x}{\sqrt{r^2+x^2}}+\frac{l-x}{\sqrt{r^2+(l-x)^2}}\right\}dx$$

$$=0.2\pi nI\left\{\sqrt{r^2+x^2}-\sqrt{r^2+(l-x)^2}\right\}_o^l$$

$$=0.4\pi nI\left\{\sqrt{r^2+l^2}-r\right\}$$

This last expression is the mmf applied to the bar.

The total mmf of the solenoid is

$$0.4\pi nIl$$

The ratio of the mmf applied to the bar to that of the solenoid is therefore

$$\frac{0.4\pi nI\{\sqrt{r^2+l^2}-r\}}{0.4\pi nIl}=\sqrt{1+\beta^2}-\beta, \text{ where } \beta=\frac{r}{l}$$

$$=1+\frac{\beta^2}{2}-\frac{\beta^4}{8}+, \text{ etc.}$$

The proportion of the total mmf applied to the yokes is the difference between the above quantity and unity; that is,

$$\beta-\frac{\beta^2}{2}+\frac{\beta^4}{8}-\text{ etc.} \qquad \text{eq. (1)}$$

In the case of the solenoid of the Koepsel apparatus

$$r_1 = 0.85$$
$$r_2 = 2.70$$
$$r_{mean} = 1.78$$
$$l = 12.7$$
$$\beta = \frac{1.78}{12.7} = 0.14$$

Substituting $\beta=0.14$ in equation (1)

we have $\beta-\frac{\beta^2}{2}+\frac{\beta^4}{8}=0.14-\frac{0.14^2}{2}+\frac{0.14^4}{8}$

$$=0.140-.010+.000$$
$$=0.13$$

that is 13 per cent of the total mmf of the solenoid is applied directly to the yokes.

This result is calculated on the assumption that the portion of the mmf applied to the yokes is the same as if the coil were concentrated in one layer at its mean radius.

10. THE MAGNETIZING FORCE

The magnetizing force acting on the center of the bar is the resultant of at least five components.

The most important is the magnetizing solenoid itself. This is the only one that can be calculated directly and it is very desirable to construct the apparatus so that all the other components of magnetizing force neutralize each other. The next best condition is to have these secondary magnetizing forces directly proportional to that exerted by the main solenoid. In the present piece of apparatus neither of these conditions is fulfilled.

The compensating coil C, Fig. 1, contributes a small demagnetizing force at the center of the bar. This is shown in the last column of Table 3 by indicating a lower actual induction in the bar when the compensation is used than when no compensation is used. This difference produces a change in induction as great as 3 per cent at low intensities and vanishes at the higher inductions. This demagnetizing force is small and may be considered as approximately 3 per cent of the total magnetizing force at the lower inductions, and is negligible at the upper values.

The magnetic field of the solenoid acts on the yokes in such a direction as to produce a positive magnetizing force in the space occupied by the test bar. This magnetizing force is proportional to the current and consequently, if plotted as abscissæ against induction as ordinates, would give a curve of the same shape as the normal B—H curve. This reactive force of the yokes has been noted before in other forms of magnetic circuit.[10]

The bar itself presents magnetic poles which exert a magnetizing force both on the bar and on the yokes. This magnetizing force opposes that due to the solenoid as far as the rod is concerned. It is this demagnetizing force which plays so important a part in straight bars with air-return magnetic circuits.

This magnetizing force acts also on the yokes, thus producing a positive magnetizing force in the region occupied by the bars. Each of these effects is proportional to the leakage from the bar, and if the resultant poles were fixed in position they might be considered as a single influence. However, the distance between the poles is a function of the permeability of the bar and increases as the permeability decreases. Consequently, we might expect the demagnetizing effect of the poles to predominate at the lower inductions where the permeability is high and the corresponding magnetizing effect of the yokes to predominate at the higher inductions where the permeability of the specimen is low. These

[10] Burrows: "The determination of magnetic induction in straight bars," this Bulletin, 6. p. 45; 1909 (Reprint No. 117).

effects would be accentuated in test specimens of larger cross section, in which the leakage is greater in magnitude, thus exerting a greater field in both the bar and the yoke.

11. FLUX DENSITY

In the Koepsel apparatus the flux density through the center of the test bar is measured in terms of the field in the gap in which the test coil swings. This field is influenced by the magnitude of the flux in the test specimen, the flux in the yokes due to the magnetizing force of the solenoid, the flux due to the compensating turns, the flux due to the current in the moving coil, and also the various leakage fluxes.

The flux through the center of the test specimen is the quantity we wish to measure, and it is desirable that this flux have a constant ratio to the field in the gap in which the coil swings. If this is true, then the instrument may be calibrated so as to read true flux densities in the bar. To do this all the other flux components must add up to zero or give a resultant which is proportional to the flux in the bar. That neither of these conditions is fulfilled is seen from the data of Table 2. The total flux through the gap is always less than the flux through the specimen, but the difference becomes relatively less as the induction increases. Accordingly, if the instrument is calibrated at low or moderate inductions the higher inductions would give a reading too high or, what is equivalent, the corresponding correction to the observed magnetizing force would become positive.

The flux due to the magnetization of the yokes by the main magnetizing solenoid is nearly proportional to the current, since the iron of the yokes is worked at comparatively low inductions. The corresponding component of the shearing curve has the shape of a normal induction curve and becomes important only at the higher inductions.

The effect of the compensating turns is to reduce the flux caught by the moving coil. This effect is nearly proportional to the current and, consequently, greater at the higher inductions. It likewise contributes to the shearing curve a component which has the same shape as a normal induction curve.

The leakage flux between the ends of the specimen is very considerable, but combines with that due to the compensating turns to produce a nearly constant ratio of leakage, as shown above.

The magnetomotive force of the moving coil is relatively small. This coil has 30 turns which, for a normal specimen, corresponds to a magnetomotive force of 11 cgs units. The total magnetomotive force of the solenoid is about 12 H cgs units. The magnetomotive force of the test coil has only a small component along the direction of the main magnetic flux. However, it is concentrated at the most effective part of the circuit and undoubtedly exerts an appreciable influence.

Another element which is a source of error in the measurement of the flux density is the determination of the constant of the instrument. An error in the determination of this constant or in the setting of the auxiliary current introduces a proportional error in the measurement of the induction. The corresponding error in the magnetizing force depends upon the relative rate of change of the magnetizing force necessary to produce this change in induction. Table 5 contains a set of normal data and the changes in magnetizing force which correspond to 1 per cent change in induction. From this table we see that a change of 1 per cent in the induction corresponds to changes in magnetizing force varying from 0.4 per cent at the maximum permeability to 9 per cent at 20 000 gausses.

TABLE 5

Showing the Percentage Variations in H Corresponding to 1 Per Cent Variation in B for Low-Carbon Steel

B gausses	H gausses	$\frac{H}{B}\times 1000$	$\frac{H}{B}\times\frac{B}{100}$	Percentage variation in H
2000	3.89	0.74	0.0148	0.38
4000	4.93	.45	.0180	.36
6000	5.96	.48	.0288	.47
8000	7.28	.77	.0616	.85
10 000	9.30	1.25	.125	1.35
12 000	13.01	2.66	.319	2.46
14 000	21.36	7.25	1.07	5.01
16 000	44.18	17.5	2.80	6.35
18 000	116.3	52.	9.36	8.1
20 000	314.3	145.	29.0	9.2

12. HYSTERESIS DATA ON THE KOEPSEL PERMEAMETER

The Koepsel permeameter may be used for the determination of the hysteresis loop as well as for the measurement of permeability. Fig. 14 shows a set of data as obtained on this apparatus, together with that obtained by the author's method. These data are for an unhardened magnet steel, but show characteristics that are found in all hysteresis determinations.

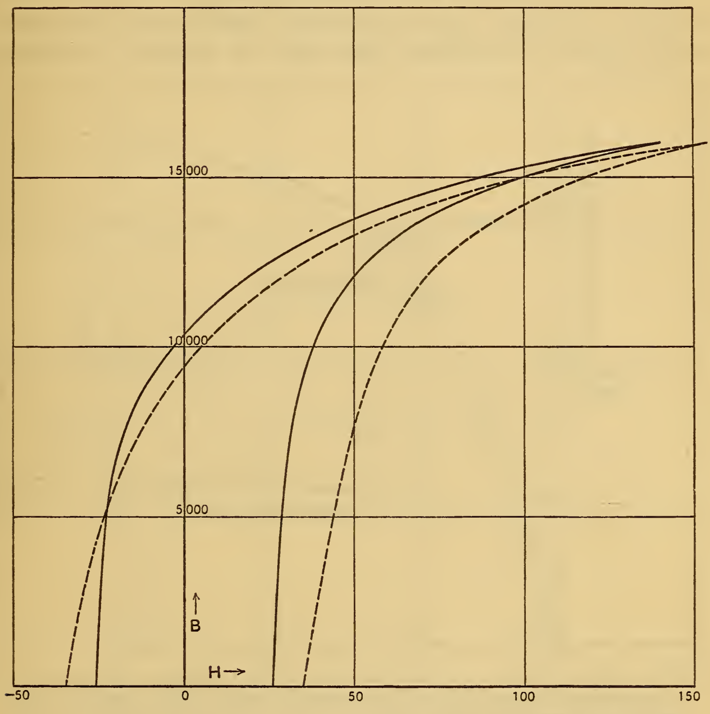

Fig. 14.—*Showing one half of a typical hysteresis loop for unhardened magnet steel as obtained by the author's method (solid line) and as obtained by the Koepsel permeameter (broken line)*

As we saw in the permeability measurements the magnetizing force corresponding to the tip of the loop is too high for the

Koepsel. The residual induction is lower and the coercive force is higher as obtained by this apparatus. The two curves intersect between the points represented by the residual induction and the coercive force.

The relation between the magnetizing forces at the tips of the curves, as obtained by the two methods, depends upon the nature of the material investigated and upon the maximum induction

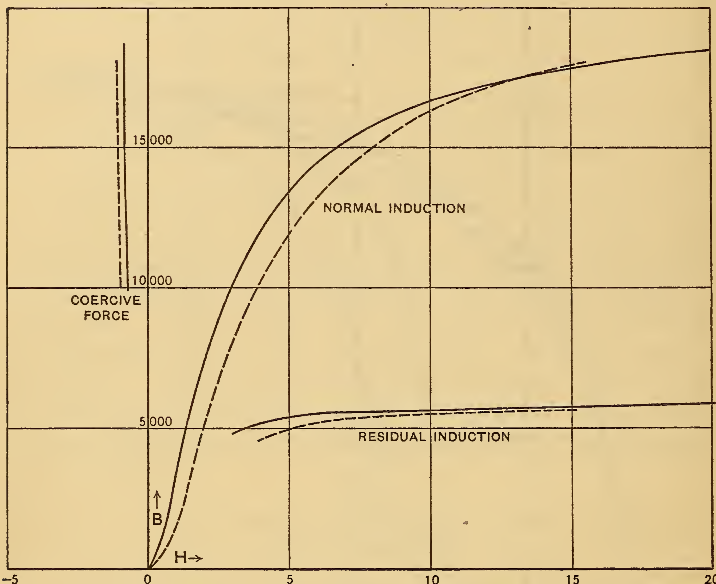

FIG. 15.—*Showing curves of normal induction, residual induction, and coercive force for a sample of low-carbon Bessemer steel as obtained by the author's method (solid line) and by the Koepsel method (broken line)*

obtained. The other characteristics are the same qualitatively for all loops of any material. Different materials differ only in degree.

On Fig. 15 are plotted the curves of maximum induction against magnetizing force, of residual induction against magnetizing force, and of coercive force against normal induction for various hysteresis loops taken with the same specimen. It is to be noticed here that the observed curve representing the tips of the loops crosses the true curve at a moderately high value. The observed residual induction curve is always lower than the true curve. The observed coercive force curve shows values of the coercive force always too large, no matter what maximum induction is used.

Figs. 16 and 17 show similar data for harder materials. From a comparison of the three figures it is evident that the residual induction as obtained on the Koepsel apparatus is always too

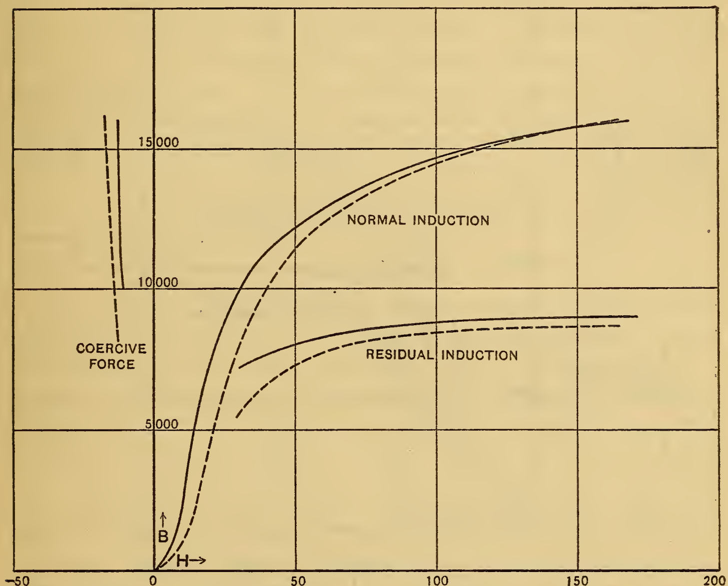

FIG. 16.—*Showing curves of normal induction, residual induction, and coercive force for a sample of tool steel as obtained by the author's method (solid line) and by the Koepsel method (broken line)*

low and that the error is greater with material having the higher inductions. The observed coercive force which gives too large a value has an increasing error as the coercive force increases.

13. THEORY OF HYSTERESIS ERRORS

The residual induction as measured may be considered as influenced by the residual magnetic fluxes in the bar, yokes, and air gaps. If these three parts of the magnetic circuit had the same remanence the reading of the instrument which measures the field in the air gap would be proportional to the residual induction in the specimen. However, this is not the case. The air gaps have no remanence, while that of the yokes may be greater or less than that of the test specimen. If it is less than the specimen, it is obvious that the mean remanence is less than that of the specimen alone. If the yokes are of hard material relative

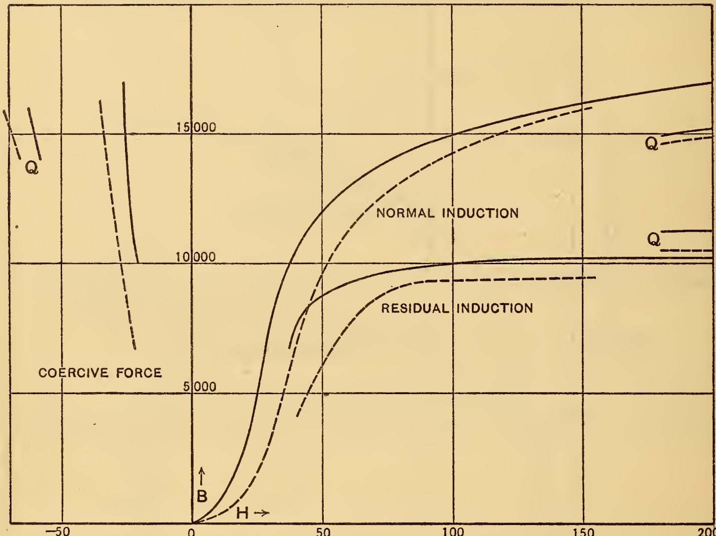

Fig. 17.—*Showing the curves of normal induction, residual induction, and coercive force for a sample of unhardened-magnet steel as obtained by the author's method (solid line) and by the Koepsel method (broken line). The short segments Q represent similar data on the same material after it has been hardened*

to the specimen, they may compensate for the lack of remanence of the air gap and we find the remanence indicated by the moving coil equal to that of the specimen or even greater than it.

The magnetomotive force which is the source of the coercive force is concentrated over the specimen itself, while the condition of no flux in the magnetic circuit is determined at a point somewhat removed from the specimen. The moving coil is in a field due to the induction in the yokes. After the whole magnetic circuit has been magnetized to a degree represented by the tip of a given hysteresis loop of the specimen and a reversed magnetizing force applied until there is no induction in the test specimen, we still have a residual induction in the yokes. This residual induction of the yokes indicates an incomplete demagnetization of the system, as shown by the pointer attached to the moving coil. To bring this pointer to zero it is necessary to magnetize the test specimen in the opposite direction. The magnetic field then due to the induction in the specimen, acts on the yokes and demagnetizes them. In this condition the instrument reads zero induction, but the test bar is magnetized in the reverse direction under a magnetizing force greater than the true coercive force. The exact nature of the error in coercive force is complicated somewhat by the influence which the magnetizing solenoid and the compensating coil exert on the yokes.

14. CONCLUSION

The Koepsel permeameter has several valuable characteristics. It gives direct readings of the magnetizing force and the magnetic induction, both for normal induction and for hysteresis data. It is easy of manipulation and does not require greater care than the usual deflection instruments. It repeats its readings as consistently as could be desired. The readings may be very useful in indicating relative values of different materials or the degree of nonuniformity of similar materials. The fact that the observed values of the magnetizing force may differ by as much as 100 per cent from the true values does not destroy the value of this instrument for purposes of comparison.

From the experimental consideration of the different factors which may affect the accuracy of the readings the following detailed conclusions were drawn:

1. Readings on the two sides of the zero of the instrument may differ considerably, but the mean of the two values thus obtained shows satisfactory consistency on repetition.

2. Shearing curves for different grades of material show that the correction to be applied to the observed magnetizing force is not constant for a given induction, but depends upon the nature of the test specimen. This correction is usually subtractive for

points below the knee of the induction curve and additive for points above the knee.

3. An increase in the cross section of the test specimen tends to increase the observed values of the magnetizing force for points below the knee of the induction curve, and to decrease the observed values for points above the knee.

4. The length of the specimen projecting beyond the yokes produces no noticeable effect for points below the knee of the induction curve. For points above the knee the projecting ends increase the observed value of the magnetizing force.

5. If the bushings are not pushed all the way into their proper position, a higher apparent value of the magnetizing force is observed, due to the increased length of the portion of the bar under test.

6. Hysteresis loops obtained by the Koepsel permeameter always show a low observed residual induction and a high observed coercive force.

7. A theoretical and experimental study of the distribution of the magnetic fluxes through different parts of the magnetic circuit shows that shearing curves of the form observed are to be expected.

If the apparatus is to be used for the determination of the absolute values of the magnetic quantities, it is necessary to apply a correction to the readings. Since the apparatus gives consistent results on repetition, the whole error may be charged to errors in the correction or shearing curve. As this shearing curve varies with the dimensions and quality of the specimen, it is essential that shearing curves be prepared for each size and quality of specimen to be tested. With extreme care and the use of proper shearing curves, the apparatus is capable of giving quantitive results within 5 per cent of the true value of the magnetizing force for a given induction.

Uncorrected hysteresis data for hard steels show values of the residual induction that are too small; the error may be as great as 10 per cent. Values obtained of the coercive force are systematically too large; the error may be as much as 40 per cent.

Washington, August 1, 1914.