DEPARTMENT OF COMMERCE
BUREAU OF STANDARDS
George K. Burgess, Director

MAGNETIC TESTING

CIRCULAR OF THE BUREAU OF STANDARDS, No. 17

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MAGNETIC QUANTITIES, UNITS, SYMBOLS, AND EQUATIONS

Magnetic Quantities and Units

Quantity	Symbol	Name of Unit
Magnetomotive force	F	gilbert
Magnetic flux	φ	maxwell
Magnetic reluctance	R	oersted
Magnetizing force	H	gilbert per cm
Magnetic induction	B	gauss
Magnetic permeability	μ	
Intensity of magnetization	J	
Magnetic susceptibility	κ	

Equations

$$F=0.4\,\pi\,NI \qquad H=\frac{dF}{dl} \qquad H=0.4\,\pi\,n\,I$$

$$e=N\frac{d\varphi}{dt}10^{-8} \qquad B=\frac{\varphi}{S} \qquad J=\frac{B-H}{4\pi}$$

$$\varphi=\frac{F}{R} \qquad \mu=\frac{B}{H} \qquad \kappa=\frac{J}{H}.$$

N = number of turns
I = current in amperes
e = electromotive force in volts
S = cross section in cm^2

n = number of turns per cm
l = length in cm
t = time in seconds

MAGNETIC TESTING

ABSTRACT

The commercial importance of magnetic testing is continually increasing. New and improved magnetic materials are being developed and more attention is being given to the specification and testing of materials used primarily for their magnetic properties. In order to promote uniformity in specification and testing of magnetic materials this circular gives a brief discussion of magnetic quantities and characteristics of materials, and outlines the various methods used by the bureau for magnetic testing.

CONTENTS

I. INTRODUCTION

The work of the Bureau of Standards in magnetic testing may be considered under three heads—(*a*) investigation and development of testing methods, (*b*) standardization of testing apparatus, and (*c*) magnetic testing of materials.

In view of the rapidly increasing amount of magnetic testing that is being done, particularly by commercial laboratories, it is very important that reliable information should be available as to the accuracy and suitability of various methods for definite purposes. There is no universal method which is applicable for all purposes, each of the methods in present use having its own peculiar limitations as to form of specimen, range of measurements, or properties of the material to be tested. In this phase of the work, therefore, it is the aim to determine the possibilities and limitations of existing methods and to develop new ones as need arises.

In the field of standardization, the work consists in the selection and preparation of suitable test specimens which, when their magnetic properties have been accurately determined, are used as magnetic standards for the calibration of testing apparatus. The proper selection and preparation of such standards is very important because errors of considerable magnitude can often be attributed to irregularities in the specimens rather than to errors inherent in the testing apparatus. It is obvious that, in such cases, erroneous conclusions may be arrived at as to the accuracy of a particular instrument or method.

A considerable amount of magnetic testing of a more or less routine nature is done in the course of investigations on the magnetic properties of materials and for outside parties requesting such tests. In the latter case, a reasonable fee is charged. The work for outside parties is limited, in general, to tests for the purpose of checking the accuracy of testing apparatus or for the settling of disputes arising from lack of agreement between different laboratories. Routine acceptance tests which can be made by commercial testing laboratories of good standing are not made by the bureau except for special reasons.

II. MAGNETIC QUANTITIES AND UNITS

The quantities most commonly used in magnetic testing are magnetomotive force, magnetic flux, magnetic reluctance, magnetizing force, magnetic induction (flux density), magnetic permeability, intensity of magnetization, and magnetic susceptibility.

1. MAGNETOMOTIVE FORCE

One common means by which objects may be magnetized is a solenoid in which an electric current is flowing. The total magnetizing influence is expressed in terms of the number of turns of wire and the value of the current. This magnetizing influence is called the magnetomotive force (F) and the cgs unit is called the gilbert. If N is the total number of turns and I is the current in amperes, then the magnetomotive force in gilberts is

$$F=0.4\ \pi\ N\ I$$

this relationship serves to define the gilbert.

2. MAGNETIC FLUX

When a substance is magnetized, it is said to carry a magnetic flux (ϕ). The cgs unit of magnetic flux is called the maxwell and its magnitude is such that when the flux linked with a single turn of wire varies at the rate of 10^8 maxwells per second, an electromotive force of 1 volt is induced in the wire. This relationship serves to define the maxwell.

3. MAGNETIC RELUCTANCE

The value of magnetic flux resulting from the influence of a given magnetomotive force is limited or determined by the magnetic reluctance (R) of the magnetic circuit. The cgs unit of magnetic reluctance is called the oersted. The relationship is expressed by the so-called Ohm's law of the magnetic circuit as follows:

$$\phi=\frac{F}{R} \text{ or maxwells}=\frac{\text{gilberts}}{\text{oersteds}}$$

This relationship serves to define the oersted.

4. MAGNETIZING FORCE

The intensity of the magnetizing influence in any given part of a magnetic circuit is called the magnetizing force (H). The magnetizing force thus defined is of the nature of a potential gradient. The cgs unit of magnetizing force is the gilbert per centimeter. At the center of a very long uniformly wound solenoid having n turns per centimeter and carrying a current of I amperes, the magnetizing force is

$$H=0.4\ \pi\ n\ I$$

5. MAGNETIC INDUCTION

Magnetic induction (B) is the density of the magnetic flux across a section normal to the direction of the flux. Across any section in which the flux is uniformly distributed, the magnetic induction in cgs units is

$$B=\frac{\phi}{S}$$

where S is the area of the section in square centimeters. The cgs unit of magnetic induction is called the gauss, and is defined from this relation.

6. MAGNETIC PERMEABILITY

The ratio of magnetic induction to the corresponding magnetizing force for any substance is called the magnetic permeability (μ).

$$\mu=\frac{B}{H} \text{ or permeability}=\frac{\text{gausses}}{\text{gilberts per cm}}$$

7. INTENSITY OF MAGNETIZATION

The degree of magnetization of a substance is sometimes expressed as the intensity of magnetization (J). No name has been assigned to the unit for this quantity. Its relation to magnetic induction is indicated by the formula

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

This unit is mainly used in expressing magnetic conditions of feebly magnetic substances.

8. MAGNETIC SUSCEPTIBILITY

The ratio of the intensity of magnetization to the magnetizing force is called the magnetic susceptibility (κ)

$$\kappa=\frac{J}{H}$$

The magnetic properties of feebly magnetic substances are generally expressed in terms of susceptibility rather than permeability.

III. MAGNETIC CHARACTERISTICS OF MATERIALS

1. CLASSIFICATION OF MATERIALS

Materials are classified with respect to their magnetic properties as either ferromagnetic, paramagnetic, or diamagnetic. Ferromagnetic materials have a magnetic permeability greater than 1 and very large; paramagnetic materials have a magnetic permeability slightly greater than 1; and diamagnetic materials have a magnetic permeability less than 1. The magnetic susceptibility of diamagnetic substances is negative. Ferromagnetic materials exhibit the phenomenon of magnetic hysteresis, which will be discussed later, and the magnetic permeability is variable, depending upon the degree of magnetization and previous treatment. The susceptibility of paramagnetic and diamagnetic substances is constant and they do not have magnetic hysteresis. Ferromagnetic materials are by far the most important from the industrial point of view.

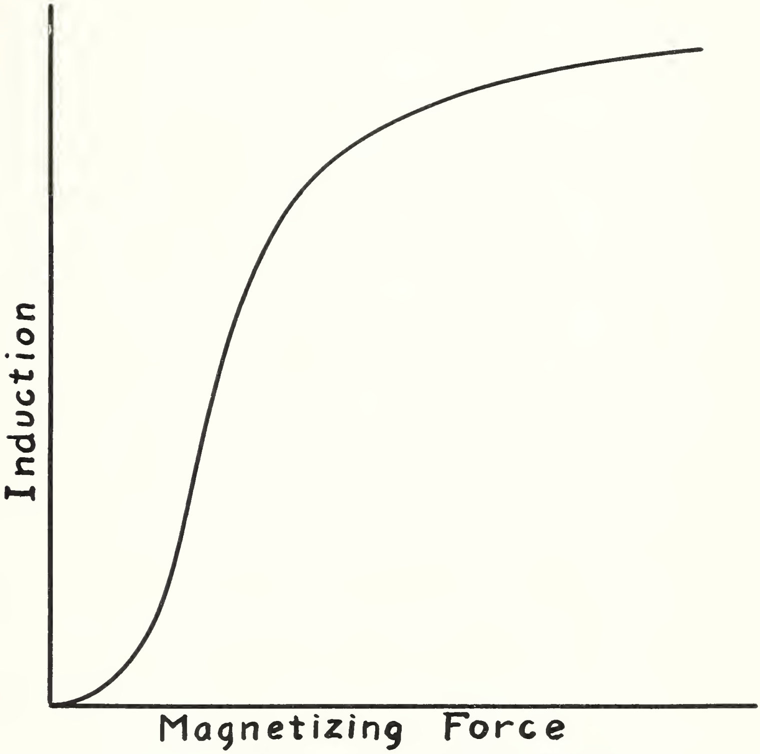

Fig. 1.—*Typical curve of magnetic induction*

2. INDUCTION

The magnetic properties of ferromagnetic materials are commonly expressed in terms of corresponding values of magnetic induction (B) and magnetizing force (H) or quantities derived from them. A typical magnetization curve is shown in Figure 1. It is to be noted that the induction is not directly proportional to the magnetizing force. In other words, the magnetic permeability does not have a single value, but depends upon the degree of magnetization. As stated above, this is characteristic of ferromagnetic substances. As the magnetizing force is increased from a zero value, the magnetization proceeds in three more or less distinct stages. In the first stage, the induction increases at a relatively slow rate with increase of magnetizing force. In the second stage, the rate of increase is much greater, while in the third stage the induction increases at a continually decreasing rate. The limits of the three stages are more or less definite according to the nature of the material.

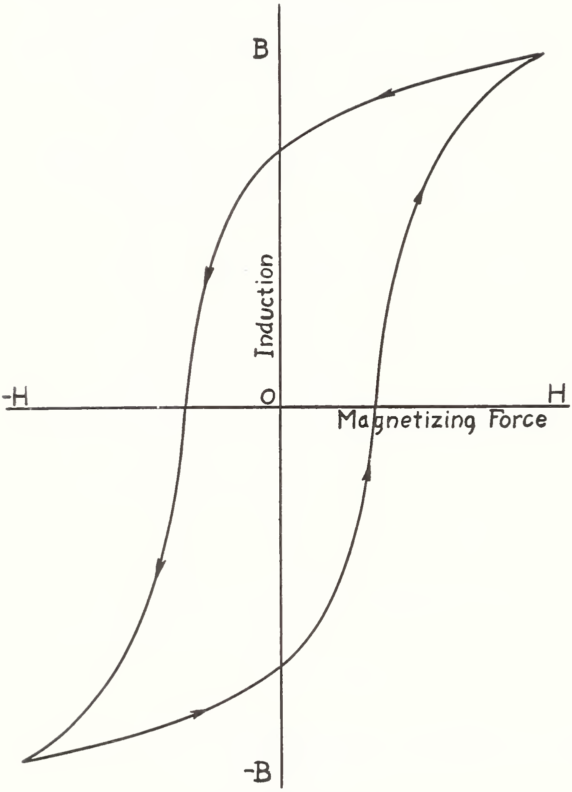

Fig. 2.—*Typical magnetic hysteresis loop*

3. HYSTERESIS

The phenomenon of magnetic hysteresis is illustrated in Figure 2. If the magnetizing force is reduced from some maximum value, the induction does not follow the magnetization curve in reverse order, but decreases in the manner indicated by the curve. When the magnetizing force has been reduced to a zero value, a certain value of induction remains. This is called the residual induction (B_r). In order to reduce the induction still further, it is necessary to apply a magnetizing force in the reverse direction. The value of reversed magnetizing force necessary to bring the induction to zero is called the coercive force (H_c). After the magnetizing force has been carried from a certain maximum value in one direction to an equal value in the opposite direction a sufficient number of times, the induction cycle becomes a closed loop, as indicated in the figure. This loop is called a hysteresis loop, and its area is proportional to the energy expended in carrying the material through a complete cycle of magnetization.

4. NORMAL INDUCTION

The induction resulting from the application of a magnetizing force of a given value depends upon the previous magnetic condition of the specimen and upon the mode of approach to the given magnetizing force; that is, the magnetization curve obtained depends upon the initial magnetic condition of the material and the manner in which the test is made. In order to obtain consistent and reproducible results, therefore, it is necessary to follow a definite procedure in making the tests. The effect of previous magnetic history, or magnetic memory as it might be termed, can be removed by demagnetization. This is accomplished by subjecting the specimen to a succession of reversals of magnetizing force gradually decreasing from a certain maximum value to one somewhat lower than the lowest at which a determination is to be made. Experiment has shown (1)[1] that demagnetization should be started from an initial value of magnetizing force well above that corresponding to maximum permeability, but not necessarily from a magnetizing force higher than any previously experienced by the specimen. After demagnetization, points on the induction curve are obtained by observing the induction resulting from the application of a given magnetizing force after a sufficient number of reversals to bring the material to a cyclic condition, thus closing up the hysteresis loop. After a determination has been made, further measurements can be made at higher values of magnetizing force without demagnetizing again, but if a lower point is desired, the demagnetization process must be repeated. Values of induction obtained in this manner are called "normal induction" and are reproducible for a given specimen within the limits of experimental error. The normal induction curve is the locus of the tips of a succession of hysteresis loops as illustrated in Figure 3.

5. NORMAL HYSTERESIS

When points on a normal hysteresis loop are to be determined, cyclic condition is first obtained by a number of reversals of the magnetizing force corresponding to the desired tip, and the induction is noted when the magnetizing force is reduced to some lower value either in the same or opposite direction. Before each determination the material is brought back to a cyclic condition by reversals of the maximum magnetizing force. This procedure differs somewhat from the "step-by-step" method, but has the advantage of giving more consistent and reliable results.

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[1] The numbers in parentheses here and throughout the text refer to the references contained in the last section of the circular.

6. CORE LOSS

When materials are subjected to alternating magnetic fields, as in the cores of transformers, a certain amount of energy is expended which can not be recovered but is dissipated in the form of heat. This loss of energy is called core loss. Core loss is made up of two components, hysteresis and eddy currents. The hysteresis loss depends upon the area of the hysteresis loop of the material and the frequency of alternations. The eddy currents are induced in the core by the varying magnetic flux and depend not only upon the frequency and maximum induction but also upon the electrical resistivity of the material, the thickness of the laminations, and the insulation between them.

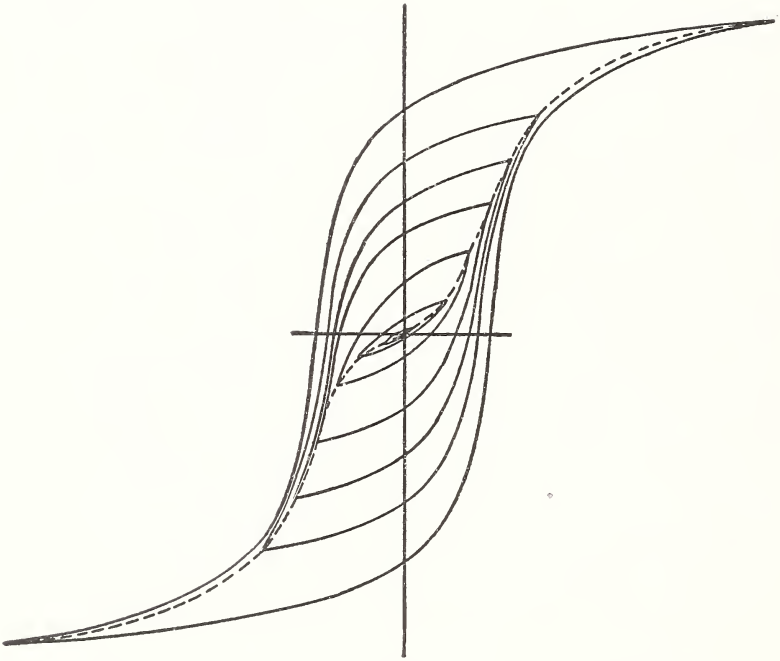

Fig. 3.—*Showing that the curve of normal induction is the locus of the tips of a family of hysteresis loops*

IV. METHODS OF MEASUREMENT

1. NORMAL INDUCTION AND HYSTERESIS

There are several different methods by which measurements of normal induction and hysteresis are ordinarily made. These methods may be classified in terms of the manner in which the magnetic induction is determined as (*a*) magnetometric, (*b*) traction, (*c*) air gap, and (*d*) ballistic.

In the magnetometric method the induction is measured in terms of the deflection of a suspended magnetic needle placed in a definite position with respect to the test sample. This method is especially suitable for observing slow changes in induction such, for instance, as occur when a specimen is heated or cooled. It has been described by Ewing (2) and by Gray and Ross (3) who used the method for determining the thermomagnetic properties of various materials. The magnetometer is a very delicate instrument and is sensitive to variations in the earth's magnetic field. It is not, therefore, to be recommended for general magnetic testing.

In the traction methods the induction is estimated in terms of the mechanical force of attraction between the surfaces of two magnetized bodies, one of which is the specimen under test. The Du Bois (4) balance is perhaps the best known of this type of permeameter. Traction permeameters require rather careful machining of the specimens and do not yield results of high accuracy. They are not in general use in the United States.

In the air-gap method the magnetic circuit is closed, except for a transverse air gap in which some measuring device, such as a deflecting coil, a rotating armature, or a bismuth spiral, is located. Perhaps the best known of this type of instrument is the Koepsel permeameter (5). This apparatus is very simple and convenient to operate, but is subject to rather large and uncertain errors, depending upon the type of materials under test.

The ballistic method is so called because it employs a ballistic galvanometer (or fluxmeter) for the determination of the value of magnetic induction. The ballistic method is used for the greater part of the magnetic testing done at the Bureau of Standards.

The ballistic method is applied in the following forms: (*a*) The Rowland ring, (*b*) the Burrows permeameter, (*c*) the straight solenoid, (*d*) the Fahy Simplex permeameter, (*e*) the magnetic comparator, and (*f*) a modification of the isthmus method.

(*a*) THE ROWLAND RING.—The magnetic circuit used in this method consists of an annular ring cut from the material to be tested. A diagram of connections is given in Figure 4. The magnetizing winding is uniformly distributed around the ring and the magnetizing force is calculated from the formula:

$$H=\frac{0.4\,\pi\,NI}{L}$$

in which

N=total number of turns,
I=current in amperes,
L=mean circumference of the ring in cm.

On account of the difference in concentration of the winding over the inner and outer part of the ring, the magnetizing force varies over the cross section causing an error in the result which depends upon the ratio of the mean diameter to the radial width of the ring (6). If this ratio is greater than 10, however, the error can usually be neglected.

The magnetic induction is determined in terms of the deflection of a ballistic galvanometer connected to a suitable test coil wound on the specimen, preferably under the magnetizing winding. Whenever there is a change in the flux linked with this test coil, an electromotive force is induced, and a certain quantity of electricity flows in the galvanometer circuit. The quantity of electricity is proportional to the change in flux. If the flux is reversed in direction by reversing the magnetizing current, the galvanometer deflection will be proportional to twice the flux.

The galvanometer is calibrated by means of a standard mutual inductance, the secondary of which is permanently connected in series with the test coil. It is usually convenient to adjust the sensitivity of the galvanometer by means of suitable series and parallel resistances so that the scale is direct reading in terms of magnetic induction. It is customary to make 1 cm deflection correspond to the reversal of an induction of 1,000 gausses. The calibrating current to be reversed in the primary of the mutual inductance depends upon the value of the mutual inductance, the number of turns in the test coil, and the cross section of the specimen, and is calculated from the following formula:

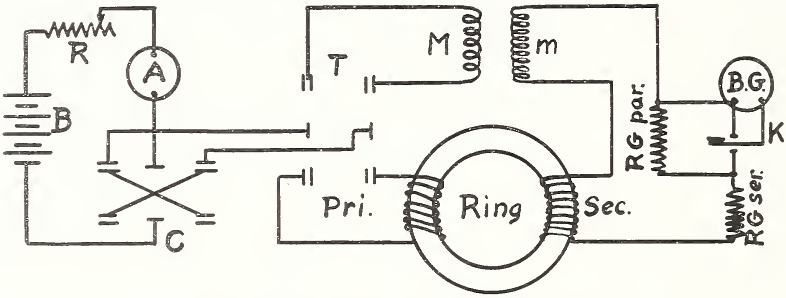

FIG. 4.—*Connections for the ring method*

$$I_c = \frac{BAN}{M \times 10^8}$$

in which

I_c=calibrating current in amperes,
B=induction in gausses.
A=cross-sectional area in cm^2,
N=number of turns in the test coil,
M=mutual inductance in henrys.

It is often convenient to use 100 turns in the test coil and to adjust the sensitivity of the galvanometer so as to have a deflection of 10 cm for a reversal of 10,000 gausses. When points on the hysteresis loop are to be determined, an auxiliary series resistance is suddenly inserted in the magnetizing circuit. In this case, care must be taken to remember that, since the galvanometer is calibrated for reversal of the induction, the readings must be multiplied by 2.

(*b*) THE BURROWS PERMEAMETER.—It is generally more convenient to prepare samples in the form of straight bars of moderate length and uniform cross section than to prepare ring specimens. There are a number of testing methods adapted to samples of this form, but the most accurate one for samples of uniform permeability along their length and having a maximum permeability, not exceeding 5,000, is the compensated double yoke method of Burrows (7). In this method auxiliary compensating coils are used to provide the extra magnetomotive force required for the yoke and joints in the magnetic circuit, and the current in them is adjusted so as to produce a uniform induction in the bar under test.

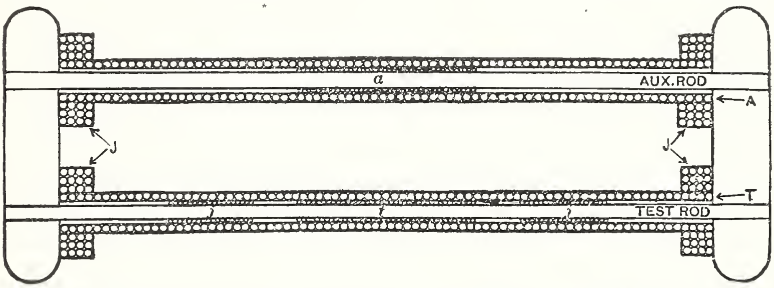

FIG. 5.—*Magnetic circuit of the Burrows permeameter showing the relative positions of the magnetizing and test coils*

Figure 5 shows the magnetic circuit of the Burrows permeameter and the relative positions of the magnetizing and test coils. The test rod and its auxiliary, which should be of the same size and material, are joined at the ends by soft-iron yokes which make good magnetic joints and complete the magnetic circuit. The magnetizing coils T and A are located over the test rod and auxiliary, respectively. Coil J is in four sections, connected in series, and located over the ends of the rods as near to the joints as possible. In operation, the currents in these three windings are so adjusted before each reading that there is equal flux in the two rods, and no leakage from the greater part of the test rod. When this condition is realized the value of the applied magnetizing force can be calculated from the current and number of turns per centimeter in the solenoid surrounding the test rod. For testing the compensation and determining the value of the induction when the compensation is properly adjusted there are three test coils designated as *t*, *a*, and *j*, respectively. These coils are each of the same number of turns and are distributed as shown in the figure; *t* is wound over the middle of the test bar, *a* over the middle of the auxiliary bar, and *j* is wound half over one end and half over the other end of the test bar far enough away from the yokes and joints to avoid disturbances from these causes. When, upon reversal of the current in the magnetizing windings, there is no residual deflection in the ballistic galvanometer whether connected to *t* and *a* or to *t* and *j* in series opposition, the magnetizing currents are properly adjusted. Under these conditions the induction is measured in terms of the deflection of the ballistic galvanometer connected to *t* alone, and the magnetizing force is proportional to the current in the winding *T*. As usually constructed, the magnetizing coil is so wound that the magnetizing force is 100 times the current in amperes. A diagram of connections is given in Figure 6. The switches *ST′*, *SA′*, and *SJ′* are for the purpose of inserting resistances in the corresponding circuits during the determination of points on the hysteresis loop. *ST′* should make contact on the forward point

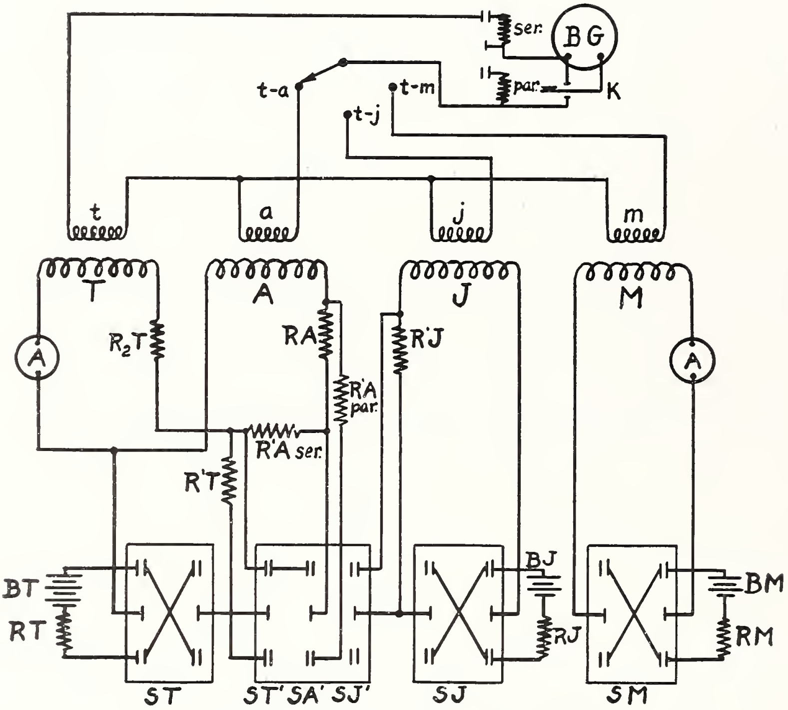

FIG. 6.—*Connections for the Burrows permeameter*

before breaking at the other. The calibration of the ballistic galvanometer is carried out as indicated for the ring method.

A correction must be made to the observed value of induction. This correction, which is necessary because of the flux in the space between the specimen and the test coil, must be applied for all ballistic methods. The amount to be subtracted from the observed value of induction is proportional to the magnetizing force and depends upon the relative areas of the test coil and specimen. It is equal to kH where

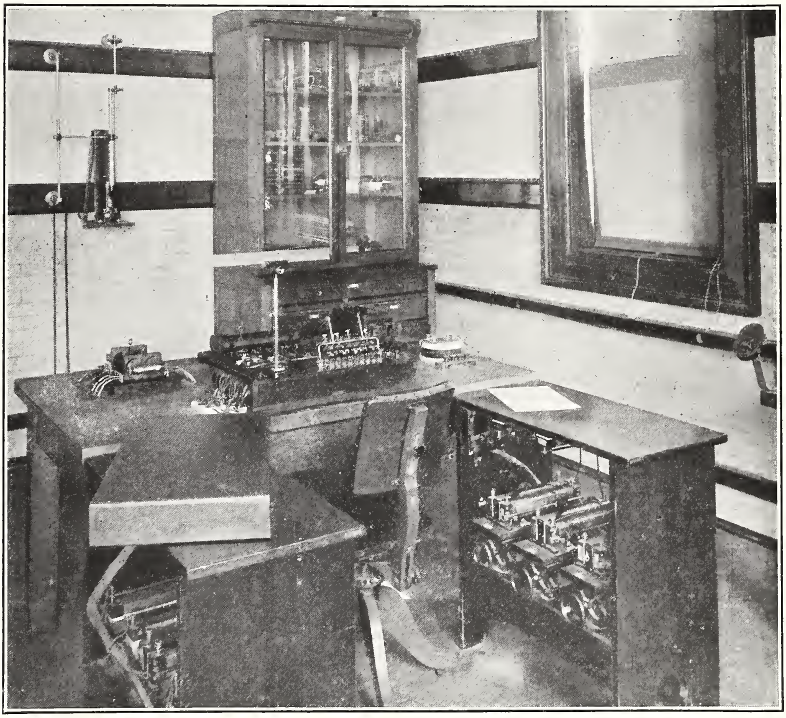

FIG. 7.—*Burrows permeameter and accessory apparatus*

$$k=\frac{a-A}{A}$$

a=area of test coil,
A=area of specimen.

Figure 7 shows the complete set-up for the Burrows permeameter. The Burrows permeameter is an absolute instrument in that its constants can be derived from measurements of its dimensions, and therefore is suitable for standardization work under proper conditions. It is, however, extremely sensitive to the influence of variations in permeability along the length of the specimen, and the results obtained on inhomogeneous materials should be interpreted with this fact in mind.

(*c*) THE STRAIGHT SOLENOID.—Sometimes it is more convenient to make measurements on a single straight bar than to prepare a ring or use the Burrows permeameter. It is difficult to obtain accurate results with this method because the magnetization of the specimen is not uniform and the free poles give rise to a self-demagnetizing effect. Uniform magnetization can be obtained by making the sample in the form of an ellipsoid of revolution, for which also the demagnetizing coefficient can be calculated. This form of specimen is not often used, however, and the demagnetizing effect for straight cylinders must be experimentally determined. The amount to be deducted from the value of the applied magnetizing force depends upon the ratio of length to diameter of the specimen and the intensity of magnetization. It has also been found that the demagnetizing coefficient is influenced by the absolute dimensions of the sample as well. The safest way is to determine the coefficient for a specimen of the same dimensions as the test sample and of approximately the same magnetic quality, although values are given in the Smithsonian Physical Tables and other tables of physical constants.

If the ratio of length to diameter is very large (200 or more), the demagnetizing effect of the ends can generally be neglected.

The procedure for making the test with a straight solenoid is substantially the same as for the ring test previously described. The correction for air flux is made as in the Burrows method.

(*d*) THE FAHY SIMPLEX PERMEAMETER.—This permeameter (fig. 8) operates on a somewhat different principle (8) than the Burrows permeameter and requires but a single specimen. The magnetizing force is applied by means of an electromagnet, across the poles of which the specimen is clamped. A uniformly wound test coil extends over the whole length of the specimen. A ballistic galvanometer connected to this test coil indicates the induction in the specimen when the magnetizing current is reversed.

The magnetizing force is measured by means of a test coil uniformly wound on a nonmagnetic form and extending between two iron blocks which are clamped to the ends of the specimen. The deflection of a ballistic galvanometer connected to such a coil when the magnetizing force is changed in value is proportional to the change in magnetic potential between the ends of the coil. The function of the iron blocks is in effect to transfer the ends of the test coil to the ends of the specimen. When the magnetic circuit is properly constructed of suitable materials, this method is capable of giving very satisfactory results. It does not require an auxiliary specimen and no compensation is necessary. It is also less sensitive than the Bur-

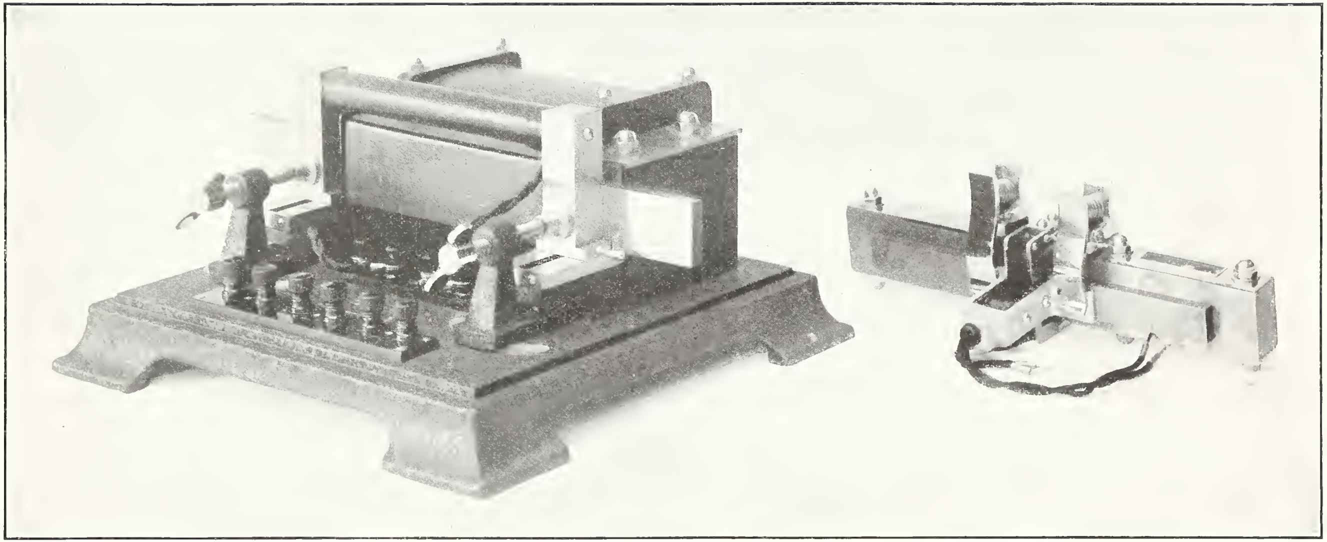

Fig. 8.—*Fahy Simplex permeameter and the high magnetization adapter*

rows permeameter to the effect of magnetic inhomogeneity along the length of the specimen. The galvanometer is calibrated by means of a standard mutual inductance as in the methods previously described and the usual correction for air flux linked with the test coil but not in the specimen is applied.

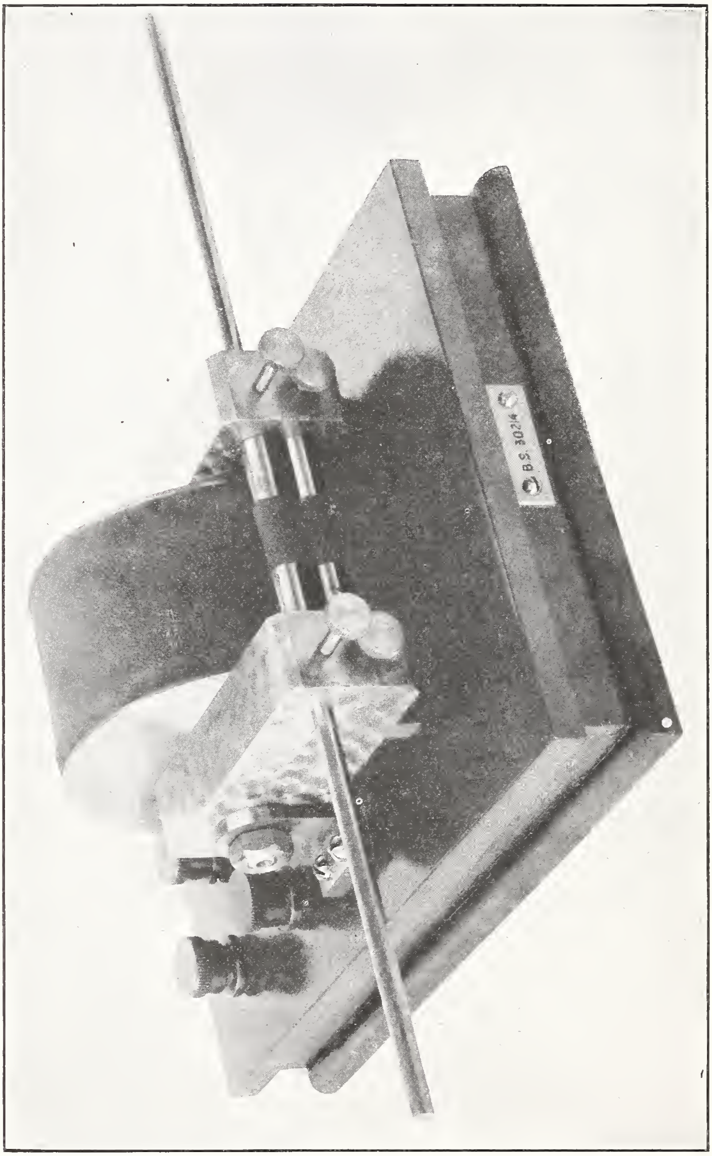

Fig. 9.—*Magnetic comparator*

By the use of an adapter for high magnetization, also shown in the photograph, the range of this permeameter may be extended up to magnetizing forces of 1,000 gilberts per centimeter or more, according to conditions. By means of the adapter the effective length of the specimen is shortened and a special test coil with iron end pieces is clamped on to the sample for the determination of the magnetizing force. The principle and procedure are the same as for the regular method.

(*e*) THE MAGNETIC COMPARATOR.—It sometimes happens that measurements are to be made on materials of which only a small quantity is available. The ordinary methods of direct measurement are not satisfactory for this purpose. A magnetic comparator, shown in Figure 9, has been devised for measurements on small samples (9). It consists of an electromagnet having holes 6 mm in diameter so located in its pole pieces that the sample under test and a reference bar can be clamped so as to be parallel to each other and about 12 mm apart. Test coils mounted on brass forms encircle each bar. With this arrangement, if there were no magnetic leakage, an equal magnetomotive force would be impressed on each bar. As a matter of fact, however, there is magnetic leakage and the magnetizing forces are not exactly equal on the two bars. In order to take this inequality into account, the apparatus is calibrated by using a standard having properties as near as possible like those of the sample to be tested. Corresponding values of induction in the reference bar and the standard, together with the magnetization curve for the standard, furnish the data for determining the magnetizing force in terms of the induction in the reference bar. The test specimen is then inserted in place of the standard and another set of corresponding values of induction observed. From these values, together with the previous calibration of the reference bar, the normal induction curve for the test specimen can be obtained. The accuracy obtainable with this method depends primarily upon the degree of similarity between the specimen and the standard used for calibration. This apparatus has proven to be very satisfactory, especially in testing pure alloys and other materials of which only small quantities could readily be prepared. Measurements have been made up to 500 gilberts per centimeter with this method with good results.

(*f*) THE MODIFIED ISTHMUS METHOD.—None of the methods described above, with the possible exception of the Fahy Simplex permeameter using the high-magnetization adapter, are suitable for measurements with very intense magnetizing fields, the range being limited by the heating of the magnetizing coils. For measurements above 100 gilberts per centimeter, a modification of the classical isthmus method of Ewing (2) has been developed (10). (Fig. 10.) The sample used in this method consists of a cylindrical bar 6 mm in diameter and at least 5 cm long.

The poles of an electromagnet of the Du Bois type are pierced coaxially so that the sample can be extended through them. The gap between the pole pieces is 2 cm long. Surrounding the specimen are two coaxial and coextensive test coils each having the same number of turns. The inner coil is of as small a diameter as possible (about 7 mm) while the outer coil has a diameter of approximately 12.5 mm.

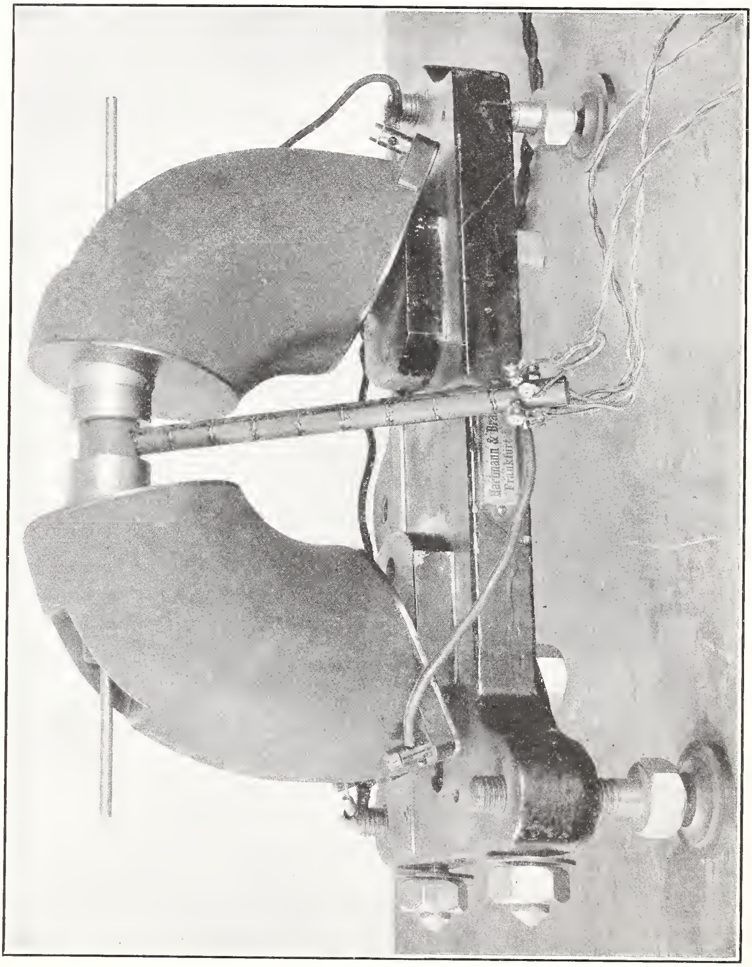

Fig. 10.—*Apparatus for testing with intense fields*

Normal induction measurements are made upon reversal of the magnetizing current. When the galvanometer is connected to the inner coil alone, the deflection on reversal is proportional to the induction in the specimen. When the galvanometer is connected to the two coils in series opposition, the deflection upon reversal is proportional to the magnetizing force. The length of the gap and the diameter of the outer test coil are so proportioned that the magnetizing field is uniform throughout the area between the two test coils.

Special switching arrangements (11) permit of the determination of points on the hysteresis loop. With this apparatus, measurements can be made in the range of magnetizing force from 100 to approximately 3,000 gilberts per centimeter.

2. CORE LOSS

For the measurement of core loss two methods are used—the Epstein method as specified by the American Society for Testing Materials and the Lloyd method developed at the bureau. The core loss apparatus used at the bureau is shown in Figure 11.

(*a*) The A. S. T. M. Method.—This method is the most commonly used one, especially for routine acceptance tests. It requires 10 kg (22 pounds) of material cut into strips 50 cm ($19\frac{11}{16}$ inches) long and 3 cm ($1\frac{3}{16}$ inches) wide. In order to take account of the difference in loss according to the direction of magnetization, half of the strips are cut parallel and half at right angles to the direction of rolling. The strips are made up into four equal bundles and inserted in four solenoids so as to form a square with butt joints. The bundles are so arranged that opposite sides of the square consist of material cut in the same manner. The strips are held in place at the corners by suitable clamps.

The solenoids have two windings, primary and secondary. An electromotive force of approximately sinusoidal wave form is applied to the primary winding and a voltmeter and the potential coil of a wattmeter are connected to the secondary winding. The wattmeter should be especially designed for low-power factors. The impressed voltage is adjusted, preferably by means of a suitable autotransformer, until the voltage of the secondary is that given by the equation:

$$E=\frac{4fNnBM}{4lD10^8}$$

in which

f=form factor of primary emf$=1.11$ for sine wave,
N=number of secondary turns,
n=frequency in cycles per second,
B=maximum induction in gausses,
M=total mass in grams,
l=length of strips in centimeters,
D=specific gravity.

In the standard test the frequency is 60 cycles per second, the maximum induction is 10,000 gausses, the mass is 10,000 grams, and the length of strips is 50 cm. The specific gravity is either measured or assumed. It is customary to assume a specific gravity of 7.5 for high-resistance steel and 7.7 for low-resistance steel.

When the voltage and frequency have been properly adjusted, the wattmeter gives the power consumed in the steel and the secondary circuit. The loss in the secondary circuit can be calculated in terms

Fig. 11.—*Apparatus for core loss testing*

of the voltage and resistance. Subtracting this correction from the total power gives the net power consumed in the steel as hysteresis and eddy-current loss. Dividing this value by 10 gives the core loss in watts per kilogram.

When tests are made under other than the standard conditions, especially if the maximum induction is carried much above 10,000 gausses, the possibility of distortion of the wave form must be taken into consideration as well as additional uncertainties from other sources.

(*b*) THE LLOYD METHOD.—Errors in the A. S. T. M. method are largely due to nonuniformity of flux distribution which results from the relatively poor magnetic joints at the corners. The Lloyd method is designed (13) to overcome this difficulty, in so far as possible, by improving the joints. Strips are cut 25.4 cm (10 inches) long and 5.1 cm (2 inches) wide and formed into a square with the strips placed on edge. Ten or twelve strips are used for each side of the square, according to the thickness of the material. The joints are improved by the insertion of right-angled corner pieces of the same or similar material. The corners are then secured with special clamps so designed as to avoid eddy currents in the clamps.

With this form of magnetic circuit, which takes from 1.5 kg (3.3 pounds) to 2 kg (4.4 pounds), the flux distribution is greatly improved, so that it is possible to make satisfactory separations of hysteresis and eddy-current losses by testing at two frequencies.

The Lloyd test is not used to any extent for general testing on account of the extra complication incident to the use of the corner pieces for which corrections must be made and the necessity for rather sensitive instruments, but is very valuable in special cases where rather complete and detailed data are required for a particular sample of material, or where data are required at higher values of maximum induction than 10,000 gausses. It is possible, for instance, to carry the induction up to about 14,000 gausses before serious wave distortion is produced.

3. SUSCEPTIBILITY

Measurements of the susceptibility of feebly magnetic substances are made chiefly to determine whether or not the materials are suitable for use in the construction of instruments and various other apparatus in which the use of magnetic materials is objectionable.

For measurements of extreme precision the Curie balance (14) or some modification thereof is necessary, but for most purposes a ballistic method, which, although less sensitive, is much more convenient to operate and is entirely adequate. In the ballistic test a straight solenoid is used having a test coil of several hundred turns mounted within it, and in which the specimen can be inserted. On account of the very low value of magnetization in the specimen, the self-demagnetizing effect is so small that it can be neglected. A variable mutual inductance is used, with its primary connected in series with the magnetizing solenoid and its secondary in series opposition with the test coil. This mutual inductance is so adjusted as to balance the mutual inductance between the solenoid and test coil. This adjustment is made with no specimen in the test coil, so that there is no deflection of the ballistic galvanometer when the primary current is reversed. The galvanometer can then be used at its maximum sensitivity. When a specimen is inserted within the test coil and the magnetizing current is reversed, the deflection of the galvanometer is proportional to the intensity of magnetization of the specimen. The magnetizing force is calculated from the current and the constants of the solenoid in the usual way, and the susceptibility is the ratio of the intensity of magnetization to the magnetizing force.

The galvanometer can be calibrated by means of the variable mutual inductance used for compensating for the test coil by reversing a known current in its primary or, preferably, by a second fixed standard of mutual inductance whose secondary is permanently connected in the galvanometer circuit.

V. MAGNETIC STANDARDS

It is not possible to realize any of the units of magnetic quantity in concrete form. Carefully selected and prepared test specimens whose magnetic properties have been accurately determined are suitable for use in the intercomparison and standardization of permeameters, however, and it may be proper, therefore, to refer to such test specimens as magnetic standards.

1. LIMITS OF ACCURACY

The problem of magnetic testing consists in determining simultaneous values of magnetic induction and magnetizing force. It is relatively easy to obtain fairly accurate values of induction, but the accurate determination of the corresponding magnetizing force is not so easy. As a matter of fact, it is only by the exercise of great care in the selection of test specimens and manipulation of the testing apparatus that an accuracy of 1 per cent can be attained. The influence of the quality and condition of the test specimen is of great importance, especially in the standardization of permeameters because inaccuracies really arising from the condition of the specimen itself should not be charged to the testing apparatus.

2. REQUIREMENTS OF STANDARD SPECIMENS

Specimens to be used as standards for the calibration of permeameters should be chosen and prepared with the following points in view: (*a*) Magnetic uniformity along the length, (*b*) metallurgical stability, and (*c*) uniformity of section.

If the specimen varies in permeability along its length, errors are introduced in the measurements which can not be calculated or eliminated by compensation, and which may be of considerable magnitude. It is not at all out of the question to have errors due to this cause alone which amount to 25 per cent or more. Moreover, various methods are sensitive to this influence in varying degrees. It is obvious, therefore, that such specimens should not be used for the intercomparison or standardizing of testing apparatus. Various methods for the determination of the degree of uniformity of magnetic test specimens have been proposed (15), but probably the most satisfactory one is to prepare a specimen much longer than is required for the final form and to make measurements at suitable intervals along its length. If the results of these measurements are in agreement, then the specimen is, from this point of view, satisfactory to use as a standard.

It is well known that specimens of steel freshly heat treated are not metallurgically stable; that is, changes in internal structure or condition may go on for some time. These changes are accompanied by corresponding changes in magnetic properties. It is necessary, therefore, to make sure that specimens to be used as magnetic standards are metallurgically stable. This can be accomplished by either natural or artificial aging. It is also desirable to repeat measurements at intervals in order to be assured that the magnetic properties are not changing.

It is quite obvious that irregularity in cross section along the length of a specimen would have an effect similar to that of a variation in magnetic permeability. For this reason it is important that care should be used in preparing the specimen to maintain a uniform cross section.

3. GENERAL PRECAUTIONS

In the calibration and use of magnetic standards it is necessary to avoid (*a*) mechanical strain, (*b*) variations in temperature, and (*c*) mechanical vibration.

Mechanical strain influences the magnetic properties of materials to a marked degree. It is important, therefore, in the calibration and use of magnetic standards that they be clamped so as to be free from strain. The effect of strain is particularly noticeable in high-permeability materials and in the lower part of the magnetization curve (16).

The effect of variations in temperature is not negligible (17), and care should be taken that standards be not heated during the course of a test. The temperature coefficient is not constant (18) and varies for different materials or even for the same material with different heat treatments.

Mechanical vibration should be avoided in magnetic testing. It has a tendency to increase the apparent permeability and to decrease the hysteresis. This is not generally a serious factor, but for work of high accuracy it should be considered and the specimens protected if necessary from excessive vibration.

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