Designation: A596/A596M − 21

Standard Test Method for Direct-Current Magnetic Properties of Materials Using the Point by Point (Ballistic) Method and Ring Specimens[1]

This standard is issued under the fixed designation A596/A596M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers dc testing for the determination of basic magnetic properties of materials in the form of ring, toroidal, link, double-lapped Epstein cores, or other standard shapes which may be cut, stamped, machined, or ground from cast, compacted, sintered, forged, or rolled materials. It includes tests for determination of the normal magnetization curve and hysteresis loop taken under conditions of steep wavefront reversals of the direct-current magnetic field strength.

1.2 This test method shall be used in conjunction with Practice A34/A34M.

1.3 This test method is suitable for a testing range from very low magnetic field strength up to 200 or more Oe [15.9 or more kA/m]. The lower limit is determined by integrator sensitivity and the upper limit by heat generation in the magnetizing winding. Special techniques and short duration testing may extend the upper limit of magnetic field strength.

1.4 Testing under this test method is inherently more accurate than other methods. When specified dimensional or shape requirements are observed, the measurements are a good approximation to absolute properties. Test accuracy available is primarily limited by the accuracy of instrumentation. In most cases, equivalent results may be obtained using Test Method A773/A773M or the test methods of IEC Publication 60404-4.

1.5 This test method permits a choice of test specimen to permit measurement of properties in any desired direction relative to the direction of crystallographic orientation without interference from external yoke systems.

1.6 The symbols and abbreviated definitions used in this test method appear in Fig. 1 and Sections 5, 6, 9, and 10. For the official definitions see Terminology A340.

1.7 **Warning—**Mercury has been designated by EPA and many state agencies as a hazardous material that can cause central nervous system, kidney, and liver damage. Mercury, or its vapor, may be hazardous to health and corrosive to materials. Caution should be taken when handling mercury and mercury-containing products. See the applicable product Material Safety Data Sheet (MSDS) for details and EPA's website (http://www.epa.gov/mercury/faq.htm) for additional information. Users should be aware that selling mercury or mercury-containing products, or both, in your state may be prohibited by state law.

1.8 The values stated in either customary (cgs-emu and inch-pound) units or SI units are to be regarded separately as standard. Within this test method, the SI units are shown in brackets except for the sections concerning calculations where there are separate sections for the respective unit systems. The values stated in each system are not exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in nonconformance with this method.

1.9 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.10 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

A34/A34M Practice for Sampling and Procurement Testing of Magnetic Materials

A340 Terminology of Symbols and Definitions Relating to Magnetic Testing

A341/A341M Test Method for Direct Current Magnetic

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[1] This test method is under the jurisdiction of ASTM Committee A06 on Magnetic Properties and is the direct responsibility of Subcommittee A06.01 on Test Methods.

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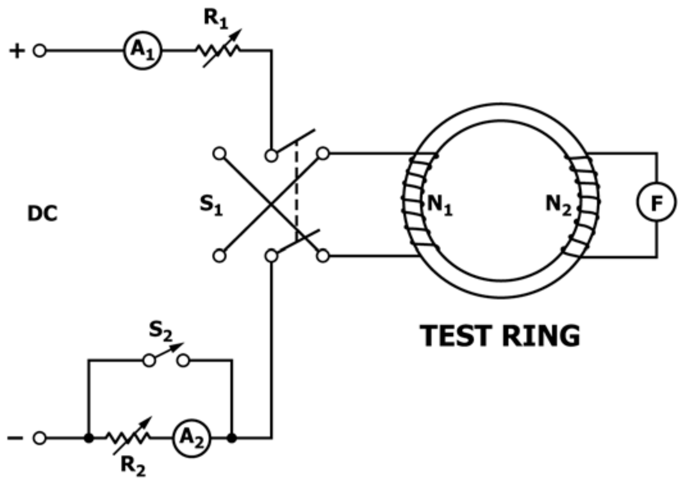
[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.



NOTE 1—
A_1—Multirange ammeter, main-magnetizing current circuit
A_2—Multirange ammeter, hysteresis-current circuit
N_1—Magnetizing (primary) winding
N_2—Flux-sensing (secondary) winding
F—Electronic integrator
R_1—Main current control rheostat
R_2—Hysteresis current control rheostat
S_1—Reversing switch
S_2—Shunting switch for hysteresis current control rheostat

FIG. 1 Basic Circuit Using Ring-Type Cores

Properties of Soft Magnetic Materials Using D-C Permeameters and the Point by Point (Ballistic) Test Methods

A343/A343M Test Method for Alternating-Current Magnetic Properties of Materials at Power Frequencies Using Wattmeter-Ammeter-Voltmeter Method and 25-cm Epstein Test Frame

A773/A773M Test Method for Direct Current Magnetic Properties of Low Coercivity Magnetic Materials Using Hysteresigraphs

2.2 *IEC Standard:*[3]

Publication 60404-4 Ed. 2.2, Magnetic Materials—Part 4: Methods of Measurement of the D-C Magnetic Properties of Magnetically Soft Materials, IEC, 2008

3. Significance and Use

3.1 Test methods using suitable ring-type specimens[4] are the preferred methods of determining the basic magnetic properties of a material caused by the absence of demagnetizing effects and are well suited for specification acceptance, service evaluation, and research and development.

3.2 Provided the test specimen is representative of the bulk material as is usually the case for thin strip and wire, this test is also suitable for design purposes.

3.3 When the test specimen is not necessarily representative of the bulk material such as a ring machined from a large forging or casting, the results of this test method may not be an accurate indicator of the magnetic properties of the bulk material. In such instances, the test results when viewed in context of past performance history will be useful for judging the suitability of the current material for the intended application.

4. Interferences

4.1 This test method has several important requirements. Unless adequate inside diameter to outside diameter ratios are maintained in the test specimens, the magnetic field strength will be excessively nonuniform throughout the test specimen and the measured parameters cannot be represented as material properties.

4.2 The basic quality of materials having directionally sensitive properties cannot be tested satisfactorily with rings or laminations. With them it is necessary to use Epstein specimens cut with their lengths in the direction of specific interest or to use long link-shaped or spirally wound toroidal core test specimens whose long dimensions are similarly located. The acceptable minimum width of strip used in such test specimens is also sensitive to the material under test. At present, it is believed that the grain-oriented silicon steels should have a strip width of at least 3 cm [30 mm].

4.3 Unless ring specimens are large in diameter, it is difficult to provide a sufficient number of primary turns needed to reach the highest magnetic field strength. In general, magnetic materials tend to have nonuniform properties throughout the body of the test specimen; for this reason, uniformly distributed test windings and uniform specimen cross-sectional area are highly desirable to suppress nonuniform behavior to a tolerable degree.

5. Apparatus

5.1 The apparatus shall consist of as many of the components described in 5.2 – 5.10 as are required to perform the desired test. The basic circuit is shown in Fig. 1.

5.2 *Balance and Scales:*

5.2.1 The balance used to weigh the test specimen shall be capable of weighing to an accuracy of better than ±0.1 % of the specimen mass.

5.2.2 The micrometer, caliper, or other length-measuring device used in the determination of magnetic path length and cross-sectional area shall be capable of measuring to an accuracy of better than ±0.1 % of the measured values.

5.3 *dc Power Supply*—The preferred source of dc current is a high-quality linear power supply of either unipolar or bipolar operation. The power supply must exhibit high stability and very low ripple to achieve the most accurate results. Programmable bipolar operational amplifier power supplies have proven to be very satisfactory for this type of testing. Other stable sources of dc current such as storage batteries are permitted.

5.4 *Main-Current-Control Rheostat R_1*—When nonprogrammable sources of dc current such as storage batteries are used, rheostats must be used to control the current. These rheostats must have sufficient power rating and heat-dissipating capability to handle the largest test current without undesirable

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[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036.

[4] Lloyd, M. G., "Errors in Magnetic Testing with Ring Specimens," *Technical News Bulletin*, National Institute for Standards and Technology, Vol 5, 1909, p. 435 (S108).

changes in resistance and, therefore, magnetizing current during conduct of the test.

5.5 *Hysteresis-Current-Control Rheostat* R_2—The hysteresis-current-control rheostat, when required, must have the same power rating and resistance as the main-current-control rheostat.

5.6 *Main-Current Ammeter* A_1—Measurement of the magnetizing current can be accomplished with either a dc ammeter or a combination of a precision shunt resistor and dc voltmeter. The meters and shunt resistor, if used, must have an accuracy of at least 0.25 %. To improve test accuracy multirange digital ammeters or voltmeters are preferred. Autoranging capability is desirable for convenience but is not essential for this test method. If analog meters are used, the ranges must be such that all test readings are made in the upper two thirds of the scale.

5.7 *Hysteresis-Current Ammeter,* A_2—The hysteresis-current measuring system shall conform to the requirements in 5.6. In general, a separate measuring system is not required since the main current ammeter (A_1) can also be used to measure the hysteresis current.

5.8 *Reversing Switch,* S_1—Because of the low resistance nature of the magnetizing circuit, it is imperative that high quality switches be used. Changes in switch resistance upon reversal will cause deviation from the cyclically magnetized condition which, if excessive, will impair test accuracy and precision. Experience has shown that mercury switches are the best suited for this application. Knife blade switches or mechanical or electrically operated contactors can also be used provided the requirement for uniform and equal contact resistance can be maintained. Because of the presence of leakage currents in the open condition, solid state relays are not permitted. The difficulties inherent in the use of main current reversing switches can be minimized by use of linear power supplies capable of accepting a remote programming signal. Such power supplies are permitted provided that the magnetizing current is equal (to within 0.1 %) in either polarity when testing in the SCM condition, current reversals can be conducted with no overshoot or oscillation and the magnetizing current is truly zero for the zero current programming signal.

5.9 *Hysteresis Switch,* S_2 *(When Required)*—This switch shall conform to requirements in 5.8.

5.10 *Integrator, F*—Because of their superior accuracy, stability, and ease of operation, electronic charge integrators are the preferred means of measuring magnetic flux. Integrators using either operational amplifier and capacitor feedback (analog integrator) or pulse counting are permitted. The accuracy of the integrator must be better than 1 % full scale. If analog display meters are used to read the value of flux, the measurement should be made on the upper two thirds of the scale. Analog integrators must have drift adjust circuitry and the drift should not exceed 100 Maxwell-turns [10^{-6} Wb-turns] per minute on the most sensitive range. It is also desirable that the integrator have appropriate scaling circuitry to permit direct reading of either magnetic flux, φ, or magnetic flux density, B.

6. Test Specimen

6.1 When the test specimen represents a test lot of material, its selection shall conform to the requirements of Practice A34/A34M or of an individual specification.

6.2 To qualify as a test specimen suitable for evaluation of material properties the effective ratio of mean diameter to radial width shall be not less than 10 to 1 (or an inside diameter to outside diameter ratio not less than 0.82). When the test specimen has smaller ratios than the above requirements, the test results should not be represented as material properties but should be called core properties because of nonuniform flux distribution.

6.3 When link, oval-shaped, or rectangular test specimen forms are used, the requirements of 6.2 apply to the end or corner sections where flux crowding occurs. When straight-sided test specimens are very long relative to the length of the corner or end sections, they are suitable for basic material properties evaluation with relatively unoriented materials provided the uncertainty in determination of true-path (effective) length is less than 5 % of the total path length. When this uncertainty in path length (shortest or longest relative to the mean-path length) exceeds 5 %, the test values should be reported as core properties and not basic material properties.

6.4 The test specimen may be constructed of solid, laminated, or strip materials and in any of the shapes described in 1.1.

6.5 Test specimen cores made from strip may be laminated, machined, spirally wound, or Epstein specimens (the method of selection for Epstein specimens is described in Test Method A343/A343M, Annex A3). When the material is to be tested half transverse and half longitudinal, the material shall be cut into Epstein strips or square laminations of adequate dimensional ratio.

6.6 Test specimens used for basic material evaluation shall be cut, machined, ground, slit, or otherwise formed to have a cross section that remains sufficiently uniform that its nonuniformity will not materially affect the accuracy of establishing and measuring magnetic flux density, B, or magnetic field strength, H, in the test specimen.

6.7 When required for material properties development, the test specimen shall have received a stress relief or other heat treatment after preparation. This heat treatment is subject to agreement between manufacturer and purchaser, manufacturer's recommendation, or the recommended heat treatment provided by the appropriate ASTM standard for the material. The heat treatment used shall be reported with the magnetic test results.

7. Calibration of Integrator

7.1 Practical operating experience has shown that provided a proper warmup period is allowed, electronic integrators require infrequent calibration. Calibration is not an integral part of this test method. When calibration is required, it can be accomplished with either a mutual inductor or a volt-second source. Because of their traceability to the fundamental units of voltage and time, volt-second sources are the preferred means of calibration. The accuracy of either the mutual inductor or volt-second source must be better than the rated full-scale accuracy of the integrator.

8. Procedure

8.1 In Fig. 1, the dc power source supplies magnetizing current measured by ammeter A_1 or A_2. Rheostats R_1 and R_2 and switches S_1 and S_2 determine the magnitude and direction of the current as required by various operations. In general, three types of switching operations are required. One is reversal of magnetizing current direction without change in magnitude as required for establishing a symmetrically cyclically magnetized (SCM) condition. This is accomplished by throwing switch S_1 from one side to the other. A second is reduction of magnitude of magnetizing current without change of polarity. This operation is required to measure points on the hysteresis loop in the first quadrant. This is done by opening switch S_2. The third operation combines reversal of magnetizing current polarity with a reduction in its magnitude. This operation is required to measure points on the hysteresis loop in the second and third quadrants. Obtain this reversal and reduction by simultaneously throwing switch S_1 from one side to the other and opening switch S_2. Use care to be sure S_2 is opened before S_1 is reclosed for reversal. When determining the hysteresis loop, switches S_1 and S_2 must be operated to traverse the loop in the same direction between successive measurements to preserve the cyclically magnetized state of the test specimen.

8.2 Demagnetize the test specimen immediately before testing. To demagnetize with direct current, first establish a magnetic field strength sufficiently large to cause the magnetic flux density in the specimen to reach a value greater than the knee of the normal magnetization curve. Then slowly reduce the magnetizing current to zero while simultaneously operating the reversing switch at one half second or longer intervals. An auxiliary circuit using a time delay relay to effect switch reversal will make this operation more reproducible and less tedious. When the test specimen consists of thin strip (<0.025 in. [0.635 mm] thick), alternating current demagnetization using 60 Hz or lower frequency and autotransformers can be used.

8.3 To obtain the magnetic flux density, B, corresponding to a specific magnetic field strength, H, establish the proper magnetizing current using Eq 1 or Eq 10, cycle the reversing switch several times to establish the symmetrically cyclically magnetized condition, zero the integrator, and execute the proper switching procedure as found in 8.1. The value of the magnetic flux density can then be computed from the integrator reading. Additional test points on the normal magnetization curve can be obtained without demagnetization if they are obtained in ascending order of B or H. Otherwise, it is necessary to demagnetize before additional testing.

8.4 To obtain the magnetic field strength corresponding to a specific magnetic flux density, a procedure similar to 8.3 is used with the exception that the magnetizing current and, therefore, magnetic field strength must be found by trial and error. If the specified magnetic flux density is exceeded, demagnetization is usually required before proceeding further unless operating at very low flux densities.

8.5 Electronic integrators do not determine magnetic flux densities directly, rather the change in flux linkages ($N_2 \Delta\varphi$) is measured. This result is converted to changes in magnetic flux density by division by the specimen cross-sectional area, A, and number of secondary turns, N_2. To determine the actual value of magnetic flux density the starting or reference points must be known. In the case of normal magnetization curve measurements, it is customary to zero the integrator and measure the change in flux density for a fully reversed change in magnetizing current. In this instance, the true value of magnetic flux density is one half of the total change in magnetic flux density. For hysteresis loop determination, the integrator is zeroed at the point of maximum magnetic flux density. The resulting change in magnetic flux density is equal to the difference in magnetic flux density between the point of maximum magnetization current and the point corresponding to the hysteresis loop measurement current.

8.6 The procedures for testing in the Epstein frame[5] are identical to those for other ring type tests.[6] The only differences are the integral air flux compensator and method of sample insertion (see Test Method A343/A343M).

9. Calculation (Customary Units)

9.1 The mean magnetic field strength applied to the test specimen by the current through the magnetizing winding is determined from the equation:

$$H = 0.4\pi NI/l_1 \tag{1}$$

where:

H = magnetic field strength, Oe;
N = number of turns in magnetizing winding N_1 of Fig. 1;
I = current through the magnetizing winding, A; and
l_1 = mean magnetic path length, cm.

9.1.1 For a ring specimen, l_1 is determined from the mean circumference. For the Epstein frame, the mean magnetic path length is assumed to be 94 cm, and this equation for the 700-turn Epstein test frame is as follows:

$$H = (0.4\pi \times 700I)/94 \tag{2}$$

$$= 9.36I$$

9.2 When test specimens have very smooth surfaces and precise uniform dimensions, the cross-sectional area may be determined by direct measurement. In all other cases, the effective test specimen cross-sectional area should be determined from measurements of mass, length, and density as follows:

$$A = m/l\delta \tag{3}$$

where:

A = test specimen cross-sectional area, cm^2;

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[5] Dieterly, D. C., "D-C Permeability Testing of Epstein Samples with Double-Lap Joints," Symposium on Magnetic Testing *ASTM STP 85*, ASTM, 1948, p. 39.

[6] Sanford, R. L. and Cooter, I. L., "Basic Magnetic Quantities and the Measurements of the Magnetic Properties of Materials," National Institute for Standards and Technology, *Monograph 47*, 1962.

m = test specimen mass, g;
l = test specimen length, cm; and
δ = density of test specimen material, g/cm^3.

9.2.1 For ring specimens, the specimen test length is assumed equal to the mean circumference so that the cross-sectional area is:

$$A = \frac{2m}{\pi(D_o+D_i)\delta} \tag{4}$$

where:

D_o = outer diameter, cm and
D_i = inner diameter, cm.

9.2.2 For the Epstein test frame:

$$A = m/(4l\delta) \tag{5}$$

where l is the length of the Epstein strips and this equation becomes:

$$A = m/(112\delta) \tag{6}$$

when $l = 28$ cm and

$$A = m/(122\delta) \tag{7}$$

when $l = 30.5$ cm.

9.3 The Epstein test frame coils are built considerably larger than the test specimen cross-sectional area. To avoid the need for manual air-flux correction, a compensating mutual inductor is built into the test frame. This means that the magnetic flux density measurements are intrinsic flux density, B_i, measurements. To obtain magnetic flux density, B, the following equation must be used:

$$B = B_i+\mu_0 H \tag{8}$$

where:

B = magnetic flux density in test specimen, G;
B_i = intrinsic flux density in test specimen, G;
H = magnetic field strength, Oe; and
μ_0 = magnetic constant = 1.

9.4 When ring testing is conducted at high magnetic field strength and particularly when the *B*-coil surrounds an appreciable air flux in addition to the core flux, the test values must be corrected for air flux as follows. Wind a duplicate set of windings around a nonmagnetic core of identical size. Connect the magnetizing windings in series aiding and the *B*-sensing windings in series opposition with the respective test-core windings. This provides air-flux compensation and the measurements become intrinsic flux density, B_i, as for the Epstein test frames. This method is usually more accurate than estimating the air-flux linking the *B*-sensing winding.

9.5 When the air flux corrections must be calculated from estimated coil areas the procedures 9.2.1 through 9.2.3 of Test Method A341/A341M should be followed.

9.6 Permeability (μ) is calculated as follows:

$$\mu = B/H \tag{9}$$

10. Calculation (SI Units)

10.1 The mean magnetic field strength applied to the test specimen by the current through the magnetizing coil is determined from the equation:

$$H = NI/l_1 \tag{10}$$

where:

H = magnetic field strength, A/m;
N = number of turns in magnetizing coil N_1 of Fig. 1;
I = current through the magnetizing coil, A; and
l_1 = mean magnetic path length, m.

10.1.1 For a ring specimen, l_1 is determined from the mean circumference. For the Epstein frame, the mean magnetic path length is assumed to be 0.94 m, and this equation for the 700-turn Epstein test frame is as follows:

$$\begin{aligned} H &= (700I)/0.94 \\ &= 745I \end{aligned} \tag{11}$$

10.2 When test specimens have very smooth surfaces and precise uniform dimensions, the cross-sectional area may be determined from physical measurements. In all other cases, the effective test specimen area should be determined from measurements of mass, length, and density as follows:

$$A = m/l\delta \tag{12}$$

where:

A = test specimen cross-sectional area, m^2;
m = test specimen mass, kg;
l = test specimen length, m; and
δ = density of test specimen material, kg/m^3.

10.2.1 For ring specimens, the specimen test length is assumed equal to the mean circumference so that the cross-sectional area is:

$$A = \frac{2m}{\pi(D_o+D_i)\delta} \tag{13}$$

where:

D_o = outer diameter, m, and
D_i = inner diameter, m.

10.2.2 For the Epstein test frame:

$$A = m/(4l\delta) \tag{14}$$

where l is the length of the Epstein strips and this equation becomes:

$$A = m/(1.12\delta) \tag{15}$$

when $l = 0.28$ m, and

$$A = m/(1.22\delta) \tag{16}$$

when $l = 0.305$ m.

10.3 The Epstein test frame coils are built considerably larger than the test specimen cross-sectional area. To avoid the need for manual air-flux correction, a compensating mutual inductor is built into the test frame. This means that the measurements are magnetic polarization, J, measurements. To obtain magnetic flux density, B, the following equation must be used:

$$B = J+\mu_0 H \tag{17}$$

where:

B = magnetic flux density in test specimen, T;
J = magnetic polarization in test specimen, T;