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Standard Test Method for Alternating-Current Magnetic Properties of Materials at Low ~~Inductions~~ Magnetic Flux Density Using the ~~Wattmeter-Varmeter-Ammeter-Voltmeter~~ Voltmeter-Ammeter-Wattmeter-Varmeter Method and 25-cm ~~[250-mm]~~ Epstein Frame[1]

This standard is issued under the fixed designation A 889/A 889M; 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 tests for the magnetic properties of basic flat-rolled magnetic materials at power frequencies ~~[25~~ (25 to 400 ~~Hz]~~ Hz) using a 25-cm ~~[250-mm]~~ Epstein test frame and the 25-cm ~~[250-mm]~~ double-lap-jointed core.

1.2 The magnetic properties of materials are determined from measurements on Epstein core specimens with the core and test coils treated as though they constituted a series-parallel equivalent circuit (Fig. A1.1) for the fundamental frequency of excitation where the apparent parallel inductance, L_1, and resistance, R_1, are attributable to the test specimen.

1.3 This test method is suitable for the determination of core loss, rms volt-amperes, rms exciting current, reactive volt-amperes, and related properties of flat-rolled magnetic materials under ac magnetization.

1.4 The frequency range of this test method is normally that of the commercial power frequencies 50 to 60 Hz. It is also acceptable for measurements at frequencies from 25 to 400 Hz. This test method is customarily used on nonoriented electrical steels at inductions up to 10 kG [1.0 T] and for grain-oriented electrical steels at inductions up to 15 kG [1.5 T].

1.5 For reactive properties, both flux and current waveforms introduce limitations. Over its range of useful inductions, the varmeter is valid for the measurement of reactive volt-amperes (vars) and inductance permeability. For the measurement of these properties, it is suggested that test inductions be limited to values sufficiently low that the measured values of vars do not differ by more than 15 % (Note 1) from those calculated from the measured values of exciting volt-amperes and core loss.

NOTE 1—This limitation is placed on this test method in consideration of the nonlinear nature of the magnetic circuit, which leads to a difference between vars based on fundamental frequency components of voltage and current and current after harmonic rejection and vars computed from rms current, voltage, and watt values when one or more of these quantities are nonsinusoidal.

1.6 This test method shall be used in conjunction with Practice A 34/A 34M.

1.7 Explanation of terms, symbols, and definitions used may be found in the various sections of this test method. The official list of definitions and symbols may be found in Terminology A 340.

~~1.8 *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 and health practices and determine the applicability of regulatory limitations prior to its use.*~~

~~1.9 The~~

1.8 The values and equations stated in ~~either~~ customary (cgs-emu and inch-pound) ~~units~~ or SI units are to be regarded separately as standard. Within ~~the text, the~~ this standard, SI units are shown in brackets. The values stated in each system ~~are~~ may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in nonconformance with this standard.

1.9 *This standard does not ~~m~~ 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 and health practices and determine the applicability of regulatory limitations prior to its use.*

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[1] This test method is under the jurisdiction of ASTM Committee ~~A-6~~ A06 on Magnetic Properties and is the direct responsibility of Subcommittee A06.01 on Test Methods.

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2. Referenced Documents

2.1 *ASTM Standards:* [2]

A 34/A 34M Practice for Sampling and Procurement Testing of Magnetic Materials

A 340 Terminology of Symbols and Definitions Relating to Magnetic Testing

A 343 Test Method for Alternating-Current Magnetic Properties of Materials at Power Frequencies Using Wattmeter-Ammeter-Voltmeter Method and 25-cm Epstein Test Frame

3. Significance and Use

3.1 This test method may be used to determine the specific core loss, specific reactive power, specific exciting power, inductance permeability, and impedance permeability of flat-rolled magnetic materials over a wide range of inductions and at frequencies up to 400 Hz for symmetrically magnetized test samples.

3.2 These measurements are used by the producer and user of the flat-rolled material for quality control purposes. The fundamental assumption inherent in these measurements is that they can be correlated with the electromagnetic characteristics of a core fabricated from the flat-rolled material.

4. Test Specimen

4.1 Select and prepare the specimens for this test in accordance with Practice A 34/A 34M.

5. Basic Circuit

5.1 Fig. 1 shows the essential apparatus and basic circuit connections for this test. Terminals 1 and 2 are connected to a source of adjustable ac voltage of sinusoidal waveform of sufficient power rating to energize the primary circuit without appreciable voltage drop in the source impedance. All primary circuit switches and all primary wiring should be capable of carrying much higher currents than are normally encountered to limit primary circuit resistance to values that will not cause appreciable distortion of the flux waveform in the specimen when relatively nonsinusoidal currents are drawn. The ac source may be an electronic amplifier which has a sine-wave oscillator connected to its input and may include the necessary circuitry to maintain a sinusoidal flux waveform by using negative feedback of the induced secondary voltage. In this case, higher primary resistance can be tolerated since this system will maintain sinusoidal flux at much higher primary resistance. Although the current drain in the secondary is quite small, especially when using modern high-input impedance instrumentation, the switches and wiring should be selected to minimize the lead resistance so that the voltage available at the terminals of the instruments is imperceptibly lower than the voltage at the secondary terminals of the Epstein test frame.

6. Apparatus

6.1 The apparatus shall consist of as many of the following component parts as are required to perform the desired measurement functions:

6.2 *Epstein Test Frame* used for this test shall be in conformity with Annex A1.1 of Test Method A 343.

6.3 *Voltage and Current Signal Scaling Amplifiers* —These amplifiers are used to amplify or attenuate the voltage induced in the secondary winding of the test frame and the voltage appearing across the potential terminals of the current shunt, R_S, to ranges that are suitable for electronic circuitry. The input circuitry of the voltage scaling amplifier must have an input impedance sufficiently high that the connection of the circuitry to the secondary winding of the test fixture does not change the terminal voltage of the secondary by more than 0.05 %. The input circuitry of the current scaling amplifier must have an input impedance

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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~~,~~ ~~Vol 03.04.~~ volume information, refer to the standard's Document Summary page on the ASTM website.

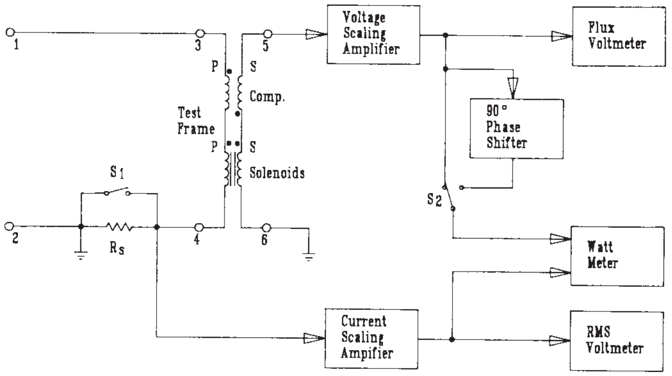

FIG. 1 Basic Circuit for Wattmeter-Varmeter Method

sufficiently high that the connection of the circuitry to the potential terminals of the current shunt does not change the terminal voltage by more than 0.05 %. These amplifiers should have a linear frequency response up to about 20 times the test frequency and a gain accuracy of 0.1 % or better since all instrumentation may be, and preferably will be, connected to the output of these amplifiers. Care should be exercised in the design of the amplifiers so that no phase shift is introduced into either the current or the voltage signal.

6.4 *Flux Voltmeter*—The flux voltmeter for this test shall be a true average-responsive voltmeter calibrated to read average volts times $\sqrt{2}\ \pi/4$, so that its indications will be identical with those of a true rms voltmeter on a pure sinusoidal voltage. A high-input-resistance, multirange electronic meter with a full-scale accuracy rating of 0.25 % or better is the preferred instrument.

6.5 *RMS Voltmeter*—A true rms-indicating voltmeter is needed if measurements of exciting current are to be made by measuring the voltage drop across the potential terminals of the current shunt. A high-input-resistance, multirange electronic instrument with a full-scale accuracy of 0.25 % or better is required for this instrument. This voltmeter may also be used to measure the true rms voltage on the secondary of the Epstein test frame.

6.6 *Wattmeter and Varmeter*—A wattmeter is required for the measurement of core loss, and a varmeter is needed for the measurement of reactive power. Since both are needed to make all measurements, the preferred instrumentation is one high-accuracy watt converter and a 90° phase-shift circuit to be used with the watt converter to measure the reactive power by shifting the phase of the secondary voltage. Alternatively, a wattmeter and a varmeter may be used as required to make the desired measurements. The rated accuracy of the wattmeter at the test frequency and unity power factor should be less than 0.25 % of full scale. The power factor encountered by the wattmeter during a core loss test on a specimen is always less than unity and, at inductions well above the knee of the magnetization curve, approaches zero. The wattmeter must maintain adequate accuracy (1 % of reading) even at the most severe (lowest) power factor which will be presented to it. The accuracy requirements for the varmeter are the same as for the wattmeter.

6.6.1 *Watt Converter and Phase Shifter*— An electronic watt converter that has two high impedance inputs and an output that is proportional to the product of the signals that are applied to these inputs is the preferred instrument for the measurement of both power and reactive power. Such devices will probably require the use of scaling amplifiers for the voltage and current signals. This device, which is used for the measurement of power, is also used for the measurement of reactive power by shifting the phase of the voltage signal by 90°. This can be done since the secondary voltage is essentially a pure sinusoid at low-to-moderate inductions, especially if negative feedback of the secondary voltage is used in the test power supply circuitry. The phase shifter that is used for this purpose should be a modern operational amplifier device which will accurately shift the phase of the input signal by exactly 90° (tolerance of 0.1°) without affecting the amplitude of the signal.

6.6.2 *Wattmeter*—An electronic wattmeter with appropriate voltage and current ratings is the preferred instrument if the separate scaling amplifiers and phase-shift circuits are not used. The voltage input circuitry of the electronic digital wattmeter must have an input impedance sufficiently high that the connection of the circuitry to the secondary winding of the test fixture does not change the terminal voltage of the secondary by more than 0.05 %. The voltage circuit must also be capable of accepting the maximum peak voltage which is induced in the secondary winding during testing. The current input circuitry of the electronic digital wattmeter must have an input impedance of no more than 1 Ω, and preferably no more than 0.1 Ω. The current input circuitry must also be capable of handling the maximum rms current and the maximum peak current drawn by the primary winding of the test fixture when core loss tests are being performed.

6.6.3 *Varmeter*—An electronic instrument with appropriate voltage and current ratings is the preferred instrument if the separate scaling amplifiers and phase-shift circuits are not used. The accuracy and impedance characteristics for the varmeter should be the same as for the wattmeter described in 6.6.2.

6.7 *Current Shunt*—This should be a noninductive resistor with an accuracy rating of 0.1 % or better. This resistor must be capable of handling the full exciting current of the test winding at the maximum test induction without destructive heating or more than specified loss of accuracy as a result of self heating. To avoid intolerable levels of distortion, the value of the resistor should be reasonably low. However, a large value of resistance is desirable to maximize the signal and reduce the effects of noise. Fixed resistors of 100, 10, and 1 Ω are useful values. The selection of shunt should be guided primarily by the primary current and should be the lowest value which retains an adequate signal-to-noise ratio.

6.8 *Power Supply*—A source of sinusoidal test power of low-internal impedance and excellent voltage and frequency stability is required for this test. Voltage stability within 0.1 % and frequency accuracy within 0.1 % should be maintained. Electronic power sources using negative feedback from the secondary winding of the test fixture to reduce flux waveform distortion have been found to perform quite satisfactorily in this test method.

7. Procedure

7.1 The first steps of procedure for this test method concern the preparations for testing Epstein specimens which are the same for this method as given in 6.1, 6.2, and 6.3 of Test Method A 343.

7.2 *Demagnetization*—Connect the required apparatus as in Fig. 1 with the air-flux compensator in the test frame and Terminals 1 and 2 connected to a suitable power source. With Switch S_1 closed in the position to short R_S, increase the voltage supplied to the test frame from zero to a value in which the flux-voltmeter indicates an induction above the knee of the magnetization curve (where the exciting current increases sharply for a small increase in induction). At this point, decrease the voltage slowly and progressively during an elapsed time of 5 to 10 s so that the induction will be reduced smoothly to a point below the lowest induction at which tests are to be performed and near zero induction. This will demagnetize the specimen which is quite important, since most highly permeable materials become polarized by handling in the earth's magnetic field during loading of the specimens into the test frame. After demagnetization, take care not to jar or move the specimen in any way that will destroy the desired reproducible (virgin) magnetic state of negligible flux density. Tests should be made immediately after demagnetization (within 2 to 3 min) for the desired test points.

7.2.1 *Core Loss, Exciting Current, and Reactive Power*— With an appropriate value for R_s inserted for the induction range to be tested (see 6.7), connect an appropriate test power source to Terminals 1 and 2. Increase the voltage supplied to the test frame until the flux voltmeter indicates that the desired test induction has been reached. Read the wattmeter to determine core loss and the rms voltmeter to determine the rms exciting current. Then position Switch S_2 to the varmeter position (90° phase shift in) and read the wattmeter again to determine the reactive power. Make tests at several inductions in order of increasing induction values.

8. Calculation (Modified cgs Units)

8.1 *Flux Volts*—The voltage induced in the specimen by the desired test induction is calculated from the following equation. This voltage is also the Voltage *E* of the equivalent circuit of Fig. A1.1 in Annex A1.

$$E = \sqrt{2}\pi B_1 A N_2 f \times 10^{-8}\ (\mathrm{V}) \tag{1}$$

where:

B_1 = maximum intrinsic flux density, G;
A = effective cross-sectional area, of test specimen, cm ^{2};
N_2 = number of turns in the secondary winding; and
f = frequency, Hz.

8.1.1 In the case of Epstein specimens, where the total number of strips is divided into four equal groups comprising the magnetic circuit, the mass of the specimen in each of the four legs becomes *m*/4, and the effective cross section, *A*, in square centimetres, of each leg is as follows:

$$A = m / 4ld \tag{2}$$

where:

m = total mass of specimen strips, g;
l = length of specimen strip, cm (usually 28 or 30.5); and
d = standard density of specimen material (see Practice A 34/A 34M), g/cm^3.

8.2 *Specific Core Loss*—To obtain the specific core loss of the specimen in watts per unit mass, it is necessary to subtract all secondary circuit power included in the wattmeter indication before dividing by the active mass of the specimen, so that for a specific induction and frequency the specific core loss in watts per pound is as follows:

$$P_{c\,(B;\,f)} = 453.6 \left(P_c - E^2 / R\right) / m_1\ (\mathrm{W/lb}) \tag{3}$$

where:

P_c = watts indicated by the wattmeter, W;
E = rms volts for the secondary circuit, V;
R = parallel resistance of all connected secondary loads, Ω; and
m_1 = active mass of specimen, g.

8.2.1 In the 25-cm Epstein frame, it is assumed that 94 cm is the effective magnetic path length with specimens 28 cm or longer. For the purpose of computing core loss, the active mass of the specimen is assumed to be as follows:

$$m_1 = l_1\ m / 4l = 94m / 4l = 23.5\ m / l\ (\mathrm{g}) \tag{4}$$

where:

m = total specimen mass, g;
l = actual strip length, cm; and
l_1 = effective magnetic path length, cm.

8.3 *RMS Exciting Current*:

8.3.1 The rms exciting current is determined by reading the voltage drop across the potential terminals of the current shunt using an electronic rms voltmeter.

8.3.2 The rms exciting current may be used to show excitation in various forms:

$$\text{rms excitation}, N_1\ I / l_1 = N_1 I / 94\ (\text{rms A}-\text{turns}/\text{cm}) \tag{5}$$

and

peak excitation, from rms current, H_z

$$\begin{aligned} H_z &= 0.4\pi\sqrt{2} N_1 I / l_1 \\ &= 0.4\pi\sqrt{2}\, N_1 I /\ 94\ (\mathrm{Oe}) \end{aligned} \tag{6}$$

where:
I = rms exciting current, A and
N_1 = number of turns in primary winding.

8.4 *Specific Exciting Power*—Specific exciting power is calculated from the rms value of current in the primary of the test frame and the rms value of the voltage induced in the secondary winding as follows:

$$P_{z\,(B;\,f)} = 453.6\,P_z / m_1 = 453.6\,EI / m_1 \text{ (rms VA/lb)} \tag{7}$$

8.5 *Specific Reactive Power*—The specific reactive power of the specimen in vars per unit mass is computed as follows:

$$P_{q\,(B;\,f)} = 453.6\,P_q / m_1 \text{ (vars/lb)} \tag{8}$$

where:
P_q = reactive power indicated by the varmeter, vars.

8.6 *Inductance Permeability*—The inductance permeability is related to the reactive component of exciting current and, thus, the reactive power as follows:

$$\mu_L = 0.625 \times 10^{-8}\, m l_1 f B_1^2 N_2^2 / d l P_q N_1^2 \tag{9}$$

8.7 *Impedance Permeability*—The impedance permeability is directly related to the rms exciting current as follows:

$$\mu_z = B_1 / H_z \tag{10}$$

9. Calculation (SI Units)

9.1 *Flux Volts*—The voltage induced in the specimen by the desired test induction is calculated from the following equation. This voltage is also the Voltage E of the equivalent circuit of Fig. A1.1 in Annex A1.

$$E = \sqrt{2}\pi B_1 A N_2 f \text{ (V)} \tag{11}$$

where:
B_1 = maximum intrinsic flux density, T;
A = effective cross-sectional area of test specimen, m^2;
N_2 = number of turns in the secondary winding; and
f = frequency, Hz.

9.1.1 In the case of Epstein specimens in which the total number of strips is divided into four equal groups comprising the magnetic circuit, the mass of the specimen in each of the four legs becomes m/4, and the effective cross section, A, in square metres, of each leg is:

$$A = m / 4ld \text{ (m}^2\text{)} \tag{12}$$

where:
m = total mass of specimen strips, kg;
l = length of specimen strip, m (usually 0.28 or 0.305); and
d = standard density of specimen material (see Practice A 34/A 34M), kg/m ^{3}.

9.2 *Specific Core Loss*—To obtain the specific core loss of the specimen in watts per unit mass, it is necessary to subtract all secondary circuit power included in the wattmeter indication before dividing by the active mass of the specimen, so that for a specific induction and frequency the specific core loss in watts per kilogram is as follows:

$$P_{c\,(B;\,f)} = (P_c - E^2/R) / m_1 \text{ (W/kg)} \tag{13}$$

where:
P_c = watts indicated by the wattmeter, W;
E = rms volts for the secondary circuit, V;
R = parallel resistance of all connected secondary loads, Ω; and
m_1 = active mass of specimen, kg.

9.2.1 In the 25-cm Epstein frame, it is assumed that 0.94 m is the effective magnetic path length with specimens 0.28 m or longer. For the purpose of computing core loss, the active mass of the specimen is assumed to be as follows:

$$m_1 = l_1 m / 4l = 0.94\,m / 4l = 0.235\,m / l \text{ (kg)} \tag{14}$$

where:
m = total specimen mass, kg;
l = actual strip length, m; and
l_1 = effective magnetic path length, m.

9.3 *RMS Exciting Current*:

9.3.1 The rms exciting current is determined by reading the voltage drop across the potential terminals of the current shunt using an electronic rms voltmeter.

9.3.2 The rms exciting current may be used to show excitation in various forms:

$$\text{rms excitation}, N_1 I / l_1 = N_1 I / 0.94 \text{ (A/m)} \tag{15}$$

and

$$\text{peak excitation, from rms current, } H_z$$

$$H_z = \sqrt{2} N_1 I / l_1 \tag{16}$$

$$= \sqrt{2} N_1 I \ / 0.94 \text{ (A/m)}$$

where:

I = rms exciting current, A and

N_1 = number of turns in primary winding.

9.4 *Specific Exciting Power*—Specific exciting power is calculated from the rms value of current in the primary of the test frame and the rms value of the voltage induced in the secondary winding as follows:

$$P_{z\,(B;\,f)} = P_z / m_1 = EI / m_1 \text{ (rms VA/kg)} \tag{17}$$

9.5 *Specific Reactive Power*—The specific reactive power of the specimen in vars per unit mass is computed as follows:

$$P_{q\,(B;\,f)} = P_q / m_1 \text{ (vars/kg)} \tag{18}$$

where:

P_q = reactive power indicated by the varmeter, vars.

9.6 *Inductance Permeability*—The inductance permeability is related to the reactive component of exciting current and, thus, the reactive power as follows:

$$\mu_L = 0.25\pi m l_1 f B_1^{\,2} N_2^{\,2} / d l P_q N_1^{\,2} \tag{19}$$

9.7 *Impedance Permeability*—The impedance permeability is directly related to the rms exciting current as follows:

$$\mu_z = B_1/H_z \tag{20}$$

10. Precision

10.1 The reproducibility of test results for core loss by this test method is estimated at ±3 % and for reactive volt-amperes, permeability, and rms exciting current ±5 %.

11. Keywords

11.1 alternating-current; ammeter; core loss; Epstein; exciting power; induction; magnetic; magnetic material; magnetic test; permeability; power frequency; varmeter; voltmeter; wattmeter

ANNEX

(Mandatory Information)

A1. BASIC THEORY OF OPERATION

A1.1 This test is based upon the fact that the primary impedance of the test winding is equivalent to a network of resistance and inductance components like that shown in Fig. A1.1. Here, without the specimen, the resistance and self-inductance of the primary test winding and leads, which are in series and carry the full exciting current, *I*, are represented by the symbols R_w and L_w, respectively. The magnetic characteristics of the specimen itself is reflected as the parallel electrical combination of ferric inductance, L_1, and ferric resistance, R_1. Although in reality L_1 and R_1 are nonlinear parameters that must vary in value throughout

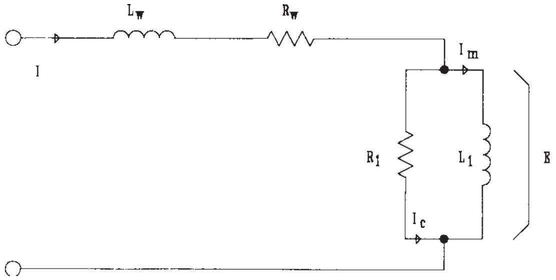

FIG. A1.1 Equivalent Circuit of Test Frame for Wattmeter-Varmeter Method the excitation cycle in such a way that the magnetizing current I_m in L_1 is that component of the exciting current necessary to produce the magnetic flux in the specimen, and the loss current I_c in R_1 is that component of the exciting current necessary to overcome the losses as a result of hysteresis and eddy currents associated with establishing the ac flux, yet the values of L_1 and R_1 during a cycle of magnetization are determined as though they were linear parameters. The voltage E across the inductive component L_1 is equal to and in phase opposition with the voltage induced by the core flux linking the test winding N_1. This voltage may be measured directly by using a high-impedance voltmeter on a secondary winding, N_2, having the same number of turns as the primary winding. Since the current components of I_m and I_c have a phase difference of 90 electrical degrees, with I_c being in phase with the voltage E, the core loss power is E^2/R_1, which may be measured with a wattmeter. The reactive or quadrature power is E^2/wL_1, which may be measured with a varmeter.

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