Designation: E 1004 – 02

Standard Practice for Determining Electrical Conductivity Using the Electromagnetic (Eddy-Current) Method [1]

This standard is issued under the fixed designation E 1004; 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 practice covers a procedure for determining the electrical conductivity of nonmagnetic metals using the electromagnetic (eddy-current) method. The procedure has been written primarily for use with commercially available direct reading electrical conductivity instruments. General purpose eddy-current instruments may also be used for electrical conductivity measurements but will not be addressed in this practice.

1.2 This practice is applicable to metals that have either a flat or slightly curved surface and includes metals with or without a thin nonconductive coating.

1.3 Eddy-current determinations of electrical conductivity may be used in the sorting of metals with respect to variables such as type of alloy, aging, cold deformation, heat treatment, effects associated with non-uniform heating or overheating, and effects of corrosion. The usefulness of the examinations of these properties is dependent on the amount of electrical conductivity change caused by a change in the specific variable.

1.4 Electrical conductivity, when evaluated with eddy-current instruments, is usually expressed as a percentage of the conductivity of the International Annealed Copper Standard (IACS). The conductivity of the Annealed Copper Standard is defined to be 0.58×10^8 S/m (100 % IACS) at 20°C.

1.5 The values stated in SI units are regarded as standard.

1.6 *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 use.*

2. Referenced Documents

2.1 *ASTM Standards:*

B 193 Test Method for Resistivity of Electrical Conductor Materials[2]

E 105 Practice for Probability Sampling of Materials[3]

E 122 Practice for Calculating Sample Size to Estimate, with a Specified Tolerable Error, the Average for Characteristic of a Lot or Process[3]

E 543 Practice for Agencies Performing Nondestructive Testing[4]

E 1316 Terminology for Nondestructive Examinations[4]

2.2 *ASNT Documents:*

Recommended Practice SNT-TC-1A for Personnel Qualification and Certification In Nondestructive Testing[5]

ANSI/ASNT-CP-189 Standard for Qualification and Certification of NDT Personnel[5]

2.3 *AIA Document:*

NAS–410 Certification and Qualification of Nondestructive Testing Personnel[6]

3. Terminology

3.1 *Definitions*—Definitions of terms relating to eddy-current examination are given in Terminology E 1316.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *temperature coefficient*—the fractional or percentage change in electrical conductivity per degree Celsius change in temperature.

4. Significance and Use

4.1 Absolute probe coil methods, when used in conjunction with reference standards of known value, provide a means for determining the electrical conductivity of nonmagnetic materials.

4.2 Electrical conductivity of a sample can be used as a means of determining: (*1*) type of metal or alloy, (*2*) type of heat treatment (for aluminum this evaluation should be used in conjunction with a hardness examination), (*3*) aging of the alloy, (*4*) effects of corrosion, and (*5*) heat damage.

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[1] This practice is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.07 on Electromagnetic Method.

Current edition approved July 10, 2002. Published September 2002. Originally published as E 1004 – 91. Last previous edition E 1004 – 99.

[2] *Annual Book of ASTM Standards*, Vol 02.03.

[3] *Annual Book of ASTM Standards*, Vol 14.02.

[4] *Annual Book of ASTM Standards*, Vol 03.03.

[5] Available from American Society for Nondestructive Testing 1711 Arlingate Plaza, PO Box 28518, Columbus, OH 43228–0518

[6] Available from Aerospace Industries Association of America, Inc., 1250 Eye St. NW, Washington, D.C. 20005.

5. Limitations

5.1 The ability to accomplish the examinations included in 4.2 is dependent on the conductivity change caused by the variable of interest. If the conductivity is a strong function of the variable of interest, these examinations can be very accurate. In some cases, however, changes in conductivity due to changes in the variable of interest may be too small to detect. The ability to isolate the variable of interest from other variables is also important. For example, if the alloy is not known, the heat treatment cannot be determined from conductivity alone.

5.2 The curve relating temper and conductivity of an aluminum alloy should be known before attempting to interpret conductivity measurements. For example, knowing alloy and heat treatment, the adequacy of the heat treatment can be estimated.

6. Basis of Application

6.1 *Personnel Qualification*:

6.1.1 If specified by the contractual agreement, personnel performing examinations to this standard shall be qualified in accordance with a nationally or internationally recognized NDT personnel qualification standard such as ANSI/ASNT-CP-189, SNT-TC-1A, NAS-410, or a similar document and certified by the employer or certifying agency, as applicable. The practice of the standard used and its applicable revision shall be specified in the contractual agreement between the using parties.

6.1.2 Qualification and certification for personnel may be reduced when the following conditions are met:

6.1.2.1 The examination will be limited to operating equipment, which displays the results in percent IACS.

6.1.2.2 A specific procedure is used that is approved by a certified Level III in accordance with 6.1.1.

6.1.2.3 Documentation of training and examination is performed to ensure that personnel are qualified. Qualified personnel are those who have demonstrated, by passing written and practical proficiency tests, that they possess the skills and job knowledge necessary to ensure acceptable workmanship.

6.2 *Qualification of Nondestructive Agencies*—If specified in the contractual agreement, NDT agencies shall be qualified and evaluated as described in Practice E 543. The applicable edition of Practice E 543 shall be specified in the contractual agreement.

6.3 The following additional items are subject to contractual agreement between the parties using or referencing this standard.

6.3.1 Timing of Examination

6.3.2 Extent of Examination

6.3.3 Reporting Criteria/Acceptance Criteria

6.3.4 Reexamination of Repaired/Reworked Items

7. Variables Influencing Accuracy

7.1 Consider the influence of the following variables to ensure an accurate evaluation of electrical conductivity.

7.1.1 *Temperature*—The instrument, probe, reference standards, and parts being examined shall be stabilized as ambient temperature prior to conductivity evaluation. When possible, examinations should be performed at room temperature (typically 70 ± 15°F).

7.1.2 *Probe Coil to Metal Coupling*—Variations in the separation between the probe coil and the surface of the sample (lift-off) can cause large changes in the instrument output signal. Instruments vary widely in sensitivity due to lift-off, and some have adjustments for minimizing it. Standardize the instrument with values at least as large as the known lift-off. Surface curvature may also affect the coupling. (Consult the manufacturer's manual for limitations on lift-off and surface curvature).

7.1.3 *Edge Effect*—Examinations should not be performed within two coil diameters of any discontinuity, such as an edge, hole, or notch. Use a shielded probe if examinations closer to the geometric features are required.

7.1.4 *Uniformity of Sample*—Variations in material properties are common and can be quite large. Discontinuities or inhomogeneities in the metal near the position of the probe coil will change the value of the measured conductivity.

7.1.5 *Surface Conditions*—Surface treatments and roughness can affect the measured conductivity value of a material. Cladding also has a pronounced effect on conductivity readings as compared to the base metal values. Procedures for determining the electrical conductivity of clad materials are not addressed in this practice. The sample surface should be clean and free of grease.

7.1.6 *Instrument Stability*—Instrument drift, noise, and non-linearities can cause inaccuracies in the measurement.

7.1.7 *Nonunique Conductivity Values*—It should be noted that two different alloys can have the same conductivity. Thus, in some cases, a measurement of conductivity may not uniquely characterize an alloy. Overheated parts and some heat-treated aluminum alloys are examples of materials that may have identical conductivity values for different heat treatments or tempers.

7.1.8 *Sample Thickness*—Eddy-current density decreases exponentially with depth (that is, distance from the metal surface). The depth at which the density is approximately 37 % (1/e) of its value at the surface is called the standard depth of penetration δ. Calculate the standard depth of penetration for nonmagnetic materials using one of the following formulas:

$$\delta = \frac{503.3}{\sqrt{f\sigma}}\,(m),\ \sigma = 1/\rho \tag{1}$$

$$\delta = \frac{K}{\sqrt{(1/\rho)\, f\mu_r}}\,(cm),\ K \simeq 50,\ \mu_r = 1 \tag{2}$$

$$\delta = \frac{1}{\sqrt{\pi\mu\sigma f}}\,(m),\ \mu = \mu_o\mu_r,\ \mu_o = 4\pi\times10^{-7},\ \mu_r = 1 \tag{3}$$

where:

σ = electrical conductivity of the sample in *S/m*,
ρ = electrical conductivity in Ω·*m*, and
f = examination frequency in Hz.

These formulas are for nonmagnetic materials when the relative permeability, μ_{rel}=1. If the thickness of the sample and the reference standards is at least 2.6δ, the effect of thickness is negligible. Smaller depths of penetration (higher frequencies) may be desirable for measuring surface effects. Depth of penetration is also a function of coil diameter. The change due to coil diameter variation is not considered in the above equation. Consult the instrument manufacturer if penetration depth appears to be a source of error in the measurement.

8. Apparatus

8.1 *Electronic Apparatus*—The electronic apparatus shall be capable of energizing the probe coil with alternating currents of suitable frequencies and power levels and shall be capable of sensing changes in the measured impedance of the coil. Equipment may include any suitable signal-processing device (phase discriminator, filter circuits, and so forth). The output may be displayed in either analog or digital readouts. Readout is normally in percent IACS although it may be scaled for readings in other units. Additional apparatus, such as computers, plotters, or printers, or combination thereof, may be used in the recording of data.

8.2 *Probe*—Probe coil designs combine empirical and mathematical design methods to choose appropriate combinations of characteristics. Many instruments use one probe coil. In instruments with several coils, the difference between coils is the coil geometry. For most conductivity instruments, the cable connecting the coil to the instrument is an integral part of the measuring circuit and the cable length should not be modified without consulting the instrument manufacturer or manual.

8.2.1 The probe coil should be designed to minimize the effect of heat transfer from hand to coil.

8.2.2 Some probe coils are designed to permit measurements closer than two coil diameters from an edge or discontinuity.

8.3 Mechanical handling apparatus for feeding the samples or moving the probe coil, or both, may be used to automate a specific measurement.

9. Standardization and Calibration

9.1 *Standardization*—Turn the instrument on and allow it sufficient time to stabilize in accordance with the manufacturer's instructions. Adjust, balance, and standardize the conductivity meter against the instrument's operational standards, and compensate the conductivity meter for surface roughness and lift-off in accordance with the manufacturer's instructions. If a lift-off adjustment is not available, determine the acceptable range of lift-off that will meet the accuracy requirements. Verify the standardization of the conductivity meter at periodic intervals (see Section 10).

9.1.1 The instrument, probe, and reference standards shall be standardized while maintaining the temperature within 5°F of the ambient temperature. It is desirable to perform the standardization at room temperature (typically 70 ± 15°F).

9.1.2 Instruments with two standardization adjustments shall be adjusted so that the known value of conductivity is obtained for both reference standards. The reference standards used should have conductivities that bracket the conductivity value of the sample.

9.1.3 Some instruments have only one standardization adjustment. In these cases the instrument should be standardized to a reference standard at one end of the range to be examined. A reference standard at the other end of the range should be examined to verify that the error is within acceptable limits over the entire range.

9.2 *Reference Standards*—Electrical conductivity reference standards are usually classified as primary, secondary, and operational standards.

9.2.1 *Primary Conductivity Standards*—These are reference standards that have been verified in terms of the fundamental units. The primary standards are kept in a laboratory environment and are used only to standardize secondary standards.

9.2.2 *Secondary Conductivity Standards*—These reference standards have a value assigned through comparison with primary standards. The primary standards used for assignment of values to these secondary standards shall have been standardized using Test Method B 193. The secondary standards are kept in a laboratory environment and are used only to calibrate operational or instrument standards.

9.2.3 *Operational Conductivity Standards*—These reference standards are standardized by comparison with secondary standards. These reference standards are used to standardize the instrument during use.

9.3 Reference standards should be examined with a relatively small coil to determine the uniformity of electrical conductivity over the surface of the standard. Both the front and the back surface should be examined for any conductivity differences that may exist. If possible, scan the surfaces at several different input signal frequencies.

9.4 Each time the reference standards are used, place the probe coil at the same position within ±6.35 mm (±0.25 in.) of the center of the standard.

9.5 Electrical conductivity reference standards are precise electrical standards and should be treated as such. Scratching of the surface of the standard may introduce measurement error. Avoid dropping or other rough handling of the standard. Keep the surface of the standard as clean as possible. Clean with a nonreactive liquid and a soft cloth or tissue. Store reference standards in a place where the temperature is relatively constant. Avoid thermal shocking of the reference standards or placing them where large temperature variations are present.

10. Procedure

10.1 Connect the required probe coil to the instrument.

10.2 Switch on the instrument and allow it to warm up for at least the length of time recommended by the manufacturer.

10.3 Ensure the temperature of all components to be as specified in 9.1.1, and that the instrument readings have stabilized.

10.4 Make all necessary setups and control adjustments in accordance with the manufacturer's recommendation.

10.5 Standardize the measurement system in accordance with 9.1. Standardize at the start of the run and at least once every hour of continuous operation or whenever improper functioning of the system is suspected.

10.6 Place the probe coil on the sample, and read the results on the display.

10.7 Verify the standardization of the instrument at the end of the examination of each lot. If the standardization is found to have exceeded the limits set by the user, re-standardize the system and reexamine all of the material examined since the last acceptable standardization (see 9.1).

11. Interpretation of Results

11.1 The results of eddy-current conductivity examination are based on the comparison of an unknown sample with one or more reference standards.

11.2 Ensure that the results are within the desired accuracy (refer to Section 7).

12. Report

12.1 The written report of an electrical conductivity measurement should contain any information about the examination setup that will be necessary to duplicate the examination at the same or some other location, plus such other items as may be agreed upon between the producer and purchaser. Specific items to be recorded should be agreed upon and determined by the using parties. Examples of items that may be recorded are as follows:

12.1.1 *Apparatus Description*:

12.1.1.1 Equipment type.

12.1.1.2 Model number.

12.1.1.3 Serial number.

12.1.1.4 Recorder type (if used).

12.1.2 *Coil*:

12.1.2.1 Size.

12.1.2.2 Type.

12.1.3 Other interconnecting apparatus.

12.1.4 Reference standards.

12.1.5 Measurement frequency.

12.1.6 *Description of Materials*:

12.1.6.1 Geometry.

12.1.6.2 Chemistry.

12.1.6.3 Heat treatment.

12.1.7 Standardization method.

12.1.8 *Temperature*:

12.1.8.1 Temperature of the reference standards.

12.1.8.2 Sample temperature.

12.1.8.3 Ambient temperature.

12.1.9 Examination procedure.

13. Precision and Bias

13.1 Measurement bias depends upon factors that include uniformity of material properties in the reference standard and sample, temperature control of the reference standards and sample, measurement techniques, and instrument stability and accuracy.

13.2 If the measurement has been done so that errors discussed in Section 7 are minimized, the most significant sources of systematic error will be in the reference standards and the instrumentation.

13.2.1 *Reference Standards*—The magnitude of the uncertainty of the reference standards, for example, $\pm 0.17 \times 10^6$ S/m (± 0.3 % IACS) is a systematic error for the measurement.

13.2.2 *Instrumentation*—Consult the manufacturer's manual to determine the instrument uncertainty which is also a systematic error.

13.3 *Temperature*—If absolute measurements of electrical conductivity are being made, the temperature coefficients of the reference standards must be known and used while standardizing the equipment. The systematic error due to temperature will then be negligible. If the coefficients are not known, values for the coefficients may be found in a physics or material sciences handbook. A calculation based on published values will give a general idea of the systematic error due to temperature.

13.4 Practices E 105 and E 122 may be consulted if *(1)* multiple measurements are made on a sample or *(2)* measurements are made on a portion of a large number of samples in order to determine the electrical conductivity of the lot.

14. Keywords

14.1 eddy-current; electrical conductivity; metal sorting; nondestructive testing