Designation: E1004 – 17

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

This standard is issued under the fixed designation E1004; 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.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope*

1.1 This test method 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 test method.

1.2 This test method 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) or Siemens/meter (S/m). 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.*

1.7 *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]

B193 Test Method for Resistivity of Electrical Conductor Materials
E10 Test Method for Brinell Hardness of Metallic Materials
E18 Test Methods for Rockwell Hardness of Metallic Materials
E105 Practice for Probability Sampling of Materials
E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process
E140 Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, Scleroscope Hardness, and Leeb Hardness
E543 Specification for Agencies Performing Nondestructive Testing
E1251 Test Method for Analysis of Aluminum and Aluminum Alloys by Spark Atomic Emission Spectrometry
E1316 Terminology for Nondestructive Examinations
E2371 Test Method for Analysis of Titanium and Titanium Alloys by Direct Current Plasma and Inductively Coupled Plasma Atomic Emission Spectrometry (Performance-Based Test Methodology)

2.2 *ASNT Documents:*[3]

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

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

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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.

[3] Available from American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Ln., Columbus, OH 43228-0518, http://www.asnt.org.

***A Summary of Changes section appears at the end of this standard**

ANSI/ASNT-CP-189 Standard for Qualification and Certification of Nondestructive Testing Personnel

2.3 *AIA Document:*[4]

NAS–410 Certification and Qualification of Nondestructive Testing Personnel

2.4 *ISO Standard:*[5]

ISO 9712 Non-Destructive Testing: Qualification and Certification of NDT Personnel

3. Terminology

3.1 *Definitions*—Definitions of terms relating to eddy current examination are given in Terminology E1316.

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, when used in conjunction with another method listed and compared to reference charts, 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, (*5*) heat damage, (*6*) temper, and (*7*) hardness.

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 If electrical conductivity measurements are used to interpret a property that is related to the electrical conductivity, the correlation curve relating the property to the electrical conductivity should be established for such use. For example, knowing alloy, conductivity, and hardness; or the conductivity, chemistry, and thermal history; or conductivity, chemistry, and tensile strength, 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 test method 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, ISO 9712 , 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.

NOTE 1—Note that NAS-410 does not require personnel certification when using direct read instruments

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 Testing Agencies*—If specified in the contractual agreement, NDT agencies shall be qualified and evaluated as described in Practice E543. The applicable edition of Practice E543 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 test method.

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 at ambient temperature prior to conductivity evaluation. When possible, examinations should be performed at room temperature (typically 20 °C).

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*—Consult manufacturer's instructions to determine equipment limitations for inspection adjacent to any

[4] Available from Aerospace Industries Association of America, Inc. (AIA), 1000 Wilson Blvd., Suite 1700, Arlington, VA 22209-3928, http://www.aia-aerospace.org.

[5] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

discontinuity. If no information regarding probe use restrictions or limitations adjacent to such discontinuities exist, examinations should not be performed within two coil diameters of any discontinuity.

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.

NOTE 2—Similar materials from various manufacturing methods (extrusion, forging, casting, rolling, machined vs. unmachined) may exhibit significant conductivity variation between processes. Eddy current conductivity meters can be affected by detecting differences in material grain structure, alloy uniformity, and internal stresses so care must be taken as this can influence accuracy.

7.1.5 *Surface Conditions*—Surface treatments and roughness can affect the measured conductivity value of a material. Conductive coatings such as cladding will have 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 test method. The sample surface should be clean and free of grease.

7.1.6 *Instrument Stability*—Instrument drift, noise, and nonlinearities 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. It is recommended, if chemistry and thermal history are unknown, that an indentation hardness test (such as Rockwell, Vickers, Brinell), accompanied by a test to determine chemistry such as Laser-Induced Breakdown Spectroscopy (LIBS), X-Ray Fluorescence (XRF), Atomic Emission Spectrometry (AES), Inductively Coupled Plasma (ICP), or Glow Discharge Mass Spectrometry (GDMS) chemical spot test or other laboratory analysis be used to identify an unknown material. Refer to Test Methods E10, E18, E1251, and E2371, and Standard Conversion Tables E140, for more information on methods for determining chemistry.

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:

$$\delta = \frac{503.3}{\sqrt{f\sigma}}(m), \sigma \quad \text{in} \quad S/m \tag{1}$$

$$\delta = \frac{50.3}{\sqrt{\mu_r f 1/\rho}}(mm), \rho \quad \text{in}\, \mu\Omega\bullet cm, \mu_r = 1 \tag{2}$$

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

$$\delta = \frac{660}{\sqrt{f\sigma}}(mm), \sigma \quad \text{in} \quad \%IACS \tag{4}$$

where:

σ = electrical conductivity of the sample,
ρ = electrical resistivity, and
f = examination frequency in Hz.

These formulas are for nonmagnetic materials when the relative permeability, μ_r=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. The eddy current density decrease with depth is also affected by the 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.

NOTE 3—When testing thin materials, stacking of the test parts may be acceptable. Similar material, preferably from the same batch or sheet, may be used to back the material being interrogated, thereby increasing the effective thickness. Stacked materials must be bare, without cladding, and fit so that they are in intimate contact at the area to be measured. The total thickness of the stacked material must be at least 2.6 standard depths of penetration.

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 the hand of the operator to the coil.

8.3 Mechanical handling apparatus for feeding the samples or moving the probe coil, or both, may be used to automate a specific measurement. In all cases, it is recommended to use appropriate fixtures to steady and stabilize the product or the probe coil to prevent variations in lift-off and subsequent variations in test results.

8.4 *Reference Standards*—Electrical conductivity reference standards are usually classified as primary, secondary, and operational standards. Reference standards shall be made from homogeneous and non-magnetic material. They must have a thickness equal or greater to 2.6 standard depth of penetration at the selected test frequency and a width and length equal to or greater than 2× the probe edge effect. Selected test frequency for standard design shall be 60kHz unless noted on standard.

8.4.1 *Primary Conductivity Standards*—These are reference standards that have been verified in terms of the fundamental units and have been standardized using Test Method B193. The primary standards are kept in a laboratory environment and are used only to standardize secondary standards. For best results these should be accurate to within 0.1% IACS of their stated value.

8.4.2 *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 B193. The secondary standards are kept in a laboratory environment and are used only to calibrate operational or instrument standards.

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

8.5 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.

8.6 Instrument shall be capable of measuring conductivity in the ranges expected. Consult manufacturers' manual to determine instrument suitability.

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 near the ambient temperature. It is desirable to perform the standardization at room temperature (typically 20 °C). If the temperature changes substantially (which is determined by the application) for the instrument, probe, part material, or ambient since standardization was performed then a restandardization shall be performed with the instrument, probe, reference standards, and parts being examined stabilized at the ambient temperature prior to continuing the examination.

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 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.

9.3 Each time the reference standards are used, place the probe coil at the same position relative to the center of the standard within ±½ of the coil diameter, not to exceed ±6.35 mm (±0.25 in.), for example: ±4 mm for an 8-mm diameter coil, or ±2 mm for a 4-mm diameter coil.

9.4 *Calibration*——It is recommended that instruments be calibrated once per year according to manufacturers' instructions.

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. Check the standardization at the start of the run and at least once every hour of continuous operation, at the end of a run, if there is a metal temperature change greater than ±5 F, or whenever improper functioning of the system is suspected. For best results, the unit should read within ±0.5% IACS of the stated value of the standards used when checking the standardization. If the values of the check standardization read outside of these limits, the operator should repeat tests starting from the last passed check standardization.

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, or after 15 minutes for small piece count lots. 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 ($\pm$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 E105 and E122 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.

13.5 The repeatability standard deviation and reproducibility of this test method are being determined.

14. Keywords

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

SUMMARY OF CHANGES

Committee E07 has identified the location of selected changes to this standard since the last issue (E1004 - 09) that may impact the use of this standard. (June 1, 2017)

(1) Editorial revisions were made throughout the document.
(2) Minor technical revisions were made throughout the document to add clarity.
(3) In Sections 2 and 6 changes were made, such as adding ISO 9712, to be consistent with Policy P-10.
(4) The equations for the skin depth were corrected and an additional equation for conductivity in % IACS was added.
(5) The discussion about the reference standards was moved from Section 9 to Section 8.
(6) Subsection 13.5 has been added to show that a study has not yet been completed for this test method. This study is ongoing and is expected to be completed before the next review of this document.
(7) Section 8.4 modified to add accuracy of reference standards.
(8) Section 8.6 added.
(9) Section 9.4 calibration added.
(10) Section 10.5 standardization modified.
(11) Section 7.1.7 added referenced standards and alternate test methods to use in addition to conductivity.
(12) Section 2.1 added additional reference standards concerning hardness and chemical composition measurement.
(13) Section 10.7 added allowances for small piece count lots.