Designation: E1004 – 23

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 materials, typically 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 nonmagnetic materials 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 nonmagnetic materials 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, health, and environmental 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 Guide 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)

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:*

[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.

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

3.2.1 *temperature coefficient, n*—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 specimen, 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 practice or standard 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 or other direct read values.

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 Specimen Coupling*—Variations in the separation between the probe coil and the surface of the specimen (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 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 Specimen*—Variations in material properties are common and can be quite large. Discontinuities or inhomogeneities in the nonmagnetic material being examined near the position of the probe coil will change the value of the measured conductivity.

NOTE 1—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 material (uncoated or unclad) values. Procedures for determining the electrical conductivity of clad materials are not addressed in this test method. The specimen 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 Conversion Tables E140, for more information on methods for determining chemistry.

7.1.8 *Specimen Thickness*—The specimen thickness can affect the electrical conductivity measurement. Eddy current density decreases exponentially with depth (that is, distance from the conducting material 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. If the thickness of the specimen 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. Consult the instrument manufacturer if penetration depth appears to be a source of error in the measurement.

7.1.8.1 If needed to confirm that the specimen thickness is sufficiently large, the standard depth of penetration for nonmagnetic materials can be calculated using one of the following formulas:

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

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

$$\delta = \frac{1}{\sqrt{\pi \mu f \sigma}}\,(m), \sigma \text{ in } S/m,\ \mu = \mu_o \mu_r,\ \mu_o = 4\pi \times 10^{-7} H/m,\ \mu_r = 1 \quad (3)$$

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

where:

μ = magnetic permeability of the specimen material,
μ_o = magnetic permeability of free space (air),
μ_r = relative magnetic permeability of the specimen material,
σ = electrical conductivity of the specimen material,
ρ = electrical resistivity of the specimen material, and
f = examination frequency in Hz.

These formulas are for nonmagnetic materials when the relative permeability, μ_r=1. The change in the standard depth of penetration due to coil diameter variation is not considered in the above equation.

7.1.8.2 When testing thin specimen materials, stacking of the specimen materials may be acceptable. Similar material, preferably from the same lot, batch, or sheet, may be used to back the specimen material being interrogated, thereby increasing the effective thickness. Stacked materials must be bare, without coatings or 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.

7.1.9 *Reference Standard Conductivity*—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. Apparatus

8.1 *Instrument*—The instrument (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 specimens 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 to or greater than 2.6 standard depth of