Designation: ~~E2338 – 17~~ E2338 – 22

Standard Practice for Characterization of Coatings Using Conformable Eddy Current Sensors without Coating Reference Standards[1]

This standard is issued under the fixed designation E2338; 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 the use of conformable eddy current sensors for nondestructive characterization of coatings without standardization on coated reference parts. It includes the following: *(1)* thickness measurement of a conductive coating on a conductive substrate, *(2)* detection and characterization of local regions of increased porosity of a conductive coating, and *(3)* measurement of thickness for nonconductive coatings on a conductive substrate or on a conductive coating. This practice includes only nonmagnetic coatings on either magnetic ($\mu \neq \mu_0$) or nonmagnetic ($\mu = \mu_0$) substrates. ~~This~~ In addition to discrete coatings on substrates, this practice can also be used to measure the effective thickness of a process-affected zone (for example, shot peened layer for aluminum alloys, alpha case for titanium ~~alloys).~~ alloys) and to assess the condition of other layered media such as joints (for example, lap joints and skin panels over structural supports). For specific types of coated parts, the user may need a more specific procedure tailored to a specific application.

1.2 Specific uses of conventional eddy current sensors are covered by Practices D7091 and E376 and the following test methods issued by ASTM: B244 and E1004. Guidance for the use of conformable eddy current sensor arrays is provided in Guide E2884.

1.3 *Units*—The values stated in SI units are to be regarded as standard. The values given in parentheses are mathematical conversions to inch-pound units that are provided for information only and are not considered standard.

1.4 *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.*

1.5 *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]

B244 Test Method for Measurement of Thickness of Anodic Coatings on Aluminum and of Other Nonconductive Coatings on Nonmagnetic Basis Metals with Eddy-Current Instruments

D7091 Practice for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to Ferrous Metals and Nonmagnetic, Nonconductive Coatings Applied to Non-Ferrous Metals

[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 ~~Nov. 1, 2017~~June 1, 2022. Published ~~November 2017~~June 2022. Originally approved in 2004. Last previous edition approved in ~~2011~~2017 as ~~E2338 - 11.~~E2338 – 17. DOI: ~~10.1520/E2338-17.~~10.1520/E2338-22.

[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

E376 Practice for Measuring Coating Thickness by Magnetic-Field or Eddy Current (Electromagnetic) Testing Methods
E543 Specification for Agencies Performing Nondestructive Testing
E1004 Test Method for Determining Electrical Conductivity Using the Electromagnetic (Eddy Current) Method
E1316 Terminology for Nondestructive Examinations
E2884 Guide for Eddy Current Testing of Electrically Conducting Materials Using Conformable Sensor Arrays

NOTE 1—See Appendix X1.

2.2 *ASNT Documents:*[3]
SNT-TC-1A Recommended Practice for Personnel Qualification and Certification In Nondestructive Testing
ANSI/ASNT-CP-189 Standard for Qualification and Certification of NDT Personnel

2.3 *AIA Standard:*
NAS 410 Certification and Qualification of Nondestructive Testing Personnel[4]

NOTE 1—See Appendix X1.

2.4 *ISO Standards:*[5]
ISO 9712 Non-destructive Testing—Qualification and Certification of NDT Personnel

3. Terminology

3.1 *Definitions*—For definitions of terms relating to this practice, refer to Terminology E1316. The following definitions are specific to the conformable sensors:, including Section C on Electromagnetic Testing, and also Guide

3.1.1 *conformable*—refers to an ability of sensors or sensor arrays to conform to nonplanar surfaces without any significant effects on the measurement results.

3.1.2 *lift-off*—normal distance from the conformable sensor winding plane to the top of the first conducting layer of the part under examination.E2884

3.1.3 *model for sensor response*—a relation between the response of the sensor (for example, transimpedance magnitude and phase or real and imaginary parts) to properties of interest, for example, electrical conductivity, magnetic permeability, lift-off, and conductive coating thickness, etc. These model responses may be obtained from database tables and may be analysis-based or empirical..

3.1.4 *depth of sensitivity*—depth to which sensor response to features or properties of interest, for example, coating thickness variations, exceeds a noise threshold.

3.1.5 *spatial half-wavelength*—spacing between the center of adjacent primary (drive) winding segments with current flow in opposite directions; this spacing affects the depth of sensitivity. Spatial wavelength equals two times this spacing. A single turn conformable circular coil has an approximate spatial wavelength of twice the coil diameter.

3.1.6 *insulating shims*—conformable insulating foils used to measure effects of small lift-off excursions on sensor response.

3.1.1 *air standardization*—*standardization, n*—an adjustment of the instrument with the sensor in air, that is, at least one spatial wavelength away from any conductive or magnetic objects, to match theresponse to air or another insulating material to match a model for the sensor response. Measurements on conductive materials after air standardization should provide absolute electrical properties and lift-off values. The performance can be verified on certified reference standards over the frequency range of interest.response in air.

3.1.1.1 *Discussion*—
It is generally sufficient for the sensor to be placed at least one spatial wavelength away from any conductive or magnetic object to provide the equivalent of response in air alone. Measurements on conductive materials after air standardization should provide absolute electrical properties and lift-off values. The performance can be verified on certified reference standards over the frequency range of interest.

3.1.2 *reference substrate standardization*—*performance verification, coated part, n*—an adjustment of the instrument to an appropriate reference substrate standard. The adjustment is to remove offsets between the model for the sensor response and at least two reference substrate measurements (for example, two measurements with different lift-offs at the same position on the standard).

~~These standards should have a known electrical conductivity that is essentially uniform with depth and should have essentially the same electrical conductivity and magnetic permeability as the substrate in the components being characterized.~~a measurement of coating electrical conductivity or thickness, or both, on a coated reference part with known properties to confirm that the coating electrical conductivity or thickness, or both, are within specified tolerances for the application.

3.1.2.1 *Discussion—*

Performance verification is a quality control procedure that does not represent standardization and should be documented in the report (see Section 9).

3.1.3 *performance verification, uncoated ~~part—~~part, n—*a measurement of electrical conductivity performed on a reference part with known properties to confirm that the electrical conductivity variation with frequency is within specified tolerances for the application. ~~When a reference standardization is performed, reference parts used for standardization should not be used for performance verification. These variations should be documented in the report (see Section 9). Performance verification is a quality control procedure recommended prior to or during measurements after standardization.~~

3.1.3.1 *Discussion—*

When a reference standardization is performed, reference parts used for standardization should not be used for performance verification. These variations should be documented in the report (see Section 9). Performance verification is a quality control procedure recommended prior to or during measurements after standardization.

~~3.1.10 *performance verification, coated part*—a measurement of coating electrical conductivity and/or thickness on a coated reference part with known properties to confirm that the coating electrical conductivity and/or thickness are within specified tolerances for the application. Performance verification is a quality control procedure that does not represent standardization and should be documented in the report (see Section 9).~~

3.1.4 *process-affected ~~zone—~~zone, n—*a region near the surface with depth less than ~~the~~ a spatial half wavelength that can be represented by a conductivity that is different than ~~that~~ the conductivity of the base ~~material, that is, substrate.~~material.

3.1.4.1 *Discussion—*

In some cases, the process affected zone near the surface of a material can be modeled as a coating on a substrate.

3.1.5 *reference substrate standardization, n—*an adjustment of the instrument response to an appropriate reference substrate standard.

3.1.5.1 *Discussion—*

The adjustment is to remove offsets between the model for the sensor response and at least two reference substrate measurements (for example, two measurements with different lift-offs at the same position on the standard). These standards should have a known electrical conductivity that is essentially uniform with depth and should have essentially the same electrical conductivity and magnetic permeability as the substrate in the components being characterized.

3.1.6 *sensor ~~footprint—~~footprint, n—*area of the sensor face placed against the material under examination.

4. Significance and Use

4.1 *Conformable Eddy Current Sensors—*Conformable, eddy current sensors can be used on both flat and curved surfaces, including fillets, cylindrical surfaces, etc. When used with models for predicting the sensor response and appropriate algorithms, these sensors can measure variations in physical properties, such as electrical conductivity ~~and/or~~or magnetic permeability, or both, as well as thickness of conductive coatings on any substrate and nonconductive coatings on conductive substrates or on a conducting coating. These property variations can be used to detect and characterize heterogeneous regions within the conductive coatings, for example, regions of locally higher porosity.

4.2 *Sensors and Sensor Arrays—*Depending on the application, either a single-sensing element sensor or a sensor array can be used for coating characterization. A sensor array ~~would provide~~ provides a better capability to map spatial variations in coating thickness ~~and/or conductivity~~ or conductivity, or both (reflecting, for example, porosity ~~variations)~~variations), and ~~provide~~provides better throughput for scanning large areas. The size of the sensor footprint and the size and number of sensing elements within an array depend on the application requirements and constraints, and the nonconductive (for example, ceramic) coating thickness.

4.3 *Coating Thickness Range—*The conductive coating thickness range over which a sensor performs best depends on the difference between the electrical conductivity of the substrate and conductive coating and available frequency range. For example, a specific sensor geometry with a specific frequency range for impedance measurements may provide acceptable performance for an MCrAlY coating over a nickel-alloy substrate for a relatively wide range of conductive coating thickness, for example, from 75 to 400 μm (0.003 to 0.016 in.). Yet, for another conductive coating-substrate combination, this range may be 10 to 100 μm (0.0004 to 0.004 in.). The coating characterization performance may also depend on the thickness of a nonconductive topcoat. For any coating system, performance verification on representative coated specimens is critical to establishing the range of optimum performance. For nonconductive coatings, such as ceramic coatings, the thickness measurement range increases with an increase of the spatial wavelength of the sensor (for example, thicker coatings can be measured with larger sensor winding spatial wavelength). For nonconductive coatings, when roughness of the coating may have a significant effect on the thickness measurement, independent measurements of the nonconductive coating roughness, for example, by profilometry, may provide a correction for the roughness effects.

4.4 *Process-Affected Zone*—For some processes, for example, shot peening, the process-affected zone can be represented by an effective layer thickness and conductivity. These values can in turn be used to assess process quality. A strong correlation must be demonstrated between these "effective coating" properties and process quality.

4.5 *Three-Unknown Algorithm*—Use of ~~multi-frequency~~multiple-frequency impedance measurements and a three-unknown algorithm permits independent determination of three unknowns: *(1)* thickness of conductive nonmagnetic coatings, *(2)* conductivity of conductive nonmagnetic coatings, and *(3)* lift-off that provides a measure of the nonconductive coating thickness.

4.6 *Accuracy*—Depending on the material properties and frequency range, there is an optimal measurement performance range for each coating system. The instrument, its air standardization ~~and/or~~or reference substrate standardization, or both, and its operation permit the coating thickness to be determined within ±15 % of its true thickness for coating thickness within the optimal range and within ±30 % outside the optimal range. Better performance may be required for some applications.

4.7 *Databases for Sensor Response*—Databases of sensor responses may be used to represent the model response for the sensor. These databases may be based upon physical models or empirical relations. The databases list expected sensor responses (for example, the real and imaginary parts or the magnitude and phase of the complex transimpedance between the sense element and drive winding) over relevant ranges in the properties of interest. Example properties for a coated substrate material are the magnetic permeability or electrical conductivity of the substrate, or both, the electrical conductivity and thickness of the coating, and the lift-off. The ranges of the property values within the databases should span the expected property ranges for the material system to be examined.

5. Interferences

5.1 *Thickness of Coating*—The precision of a measurement can change with coating thickness. The thickness of a coating should be less than the maximum depth of sensitivity. Ideally, the depth of sensitivity at the highest frequency should be less than the conductive coating thickness, while the depth of sensitivity at the lowest frequency should be significantly greater than the conductive coating thickness. The number of frequencies used in the selected frequency range should be sufficient to provide a reliable representation of the frequency-response shape.

5.2 *Thickness of Substrate*—The thickness of the substrate should be larger than the depth of sensitivity at the lowest frequency. Otherwise, this thickness must be known and accounted for in the model for the sensor response.

5.3 *Magnetic Permeability and Electrical Conductivity of Base Metal (Substrate)*—The magnetic permeability and electrical conductivity of the substrate can affect the measurement and must be known prior to coating characterization unless they can be determined independently on a coated part. When the substrate properties vary spatially, this variation must be determined as part of the coating characterization on a noncoated part that preferably has the same thermal history as the coated parts. Original uncoated parts may have significantly different microstructure than heat treated coated substrates. Uncoated colder regions of otherwise coated parts may have different properties than the coated substrate due to changes during coating and heat treatment, and, thus, may or may not be reasonably representative of the substrate under the coating. In the case these variations are consistent from component to component, a reference standard essentially equivalent to the actual substrate must be used. Differences between the actual substrate values at any coating measurement location and the values assumed for property estimation, for example, in the sensor response model, may produce errors in coating property estimates.

5.4 *Electrical Conductivity of Coating*—The precision of a measurement can change with the electrical conductivity of the coating. The electrical conductivity of the coating should be substantially different from the conductivity of the substrate. For a nonmagnetic coating on a nonmagnetic substrate, if the electrical conductivities are essentially the same, reliable coating thickness measurements cannot be obtained since the coating and substrate are electromagnetically indistinguishable. The electrical conductivity of the coating should also be large enough for sufficient eddy currents to be induced to affect the sensor response.

5.5 *Edge Effect*—Examination methods may be sensitive to abrupt surface changes of specimens or parts. Therefore, measurements made too near an edge (see 8.5.1) or inside corner may not be valid or may be insufficiently accurate unless the instrument is used with a procedure that specifically addresses such a measurement. Edge-effect correction procedures must either account for edge effects in the property estimation algorithm (for example, in the sensor response model) or incorporate careful standardization on reference parts with fixtures to control sensor position relative to the edge.

5.6 *Curvature of Examination Surface*—For surfaces with a single radius of curvature (for example, cylindrical or conical), the radius of curvature should be large compared to the sensor half-wavelength. In the case of a double curvature, at least one of the radii should significantly exceed the sensor footprint and the other radius should be at least comparable to the sensor footprint, unless customized sensors are designed to match the double curvature. Performance verification tests should be run to verify lift-off sensitivity using insulating shims.

5.7 *Instrument Stability*—Drift and noise in the instrumentation can cause inaccuracies in the measurement. Restandardization and performance verifications on at least one uncoated and one to two coated reference parts should be performed as needed to maintain required performance levels.

5.8 *Surface Roughness Including That of Base Metal*—Since a rough surface may make single measurements inaccurate, a greater number of measurements will provide an average value that is more ~~truly~~ representative of the overall coating thickness. These repeat measurements should be performed in a "pick-and-place" mode, completely removing the sensor from the surface between measurements. Coating surface roughness also may result in overestimated ceramic layer thickness or any other nonconducting coating thickness since the probe may rest on peaks.

5.9 *Directionality of Base-Metal Properties*—Measurements may be sensitive to anisotropy of the base metal due to the fabrication process, for example, rolling, directional solidification, single-crystal growth, etc. It is essential to keep the alignment of sensor/probe consistent throughout the standardization step and measurements on a given part and from part to part.

5.10 *Residual Magnetism in Base Metal*—Residual magnetism in coating/substrate may affect accuracy of measurement.

5.11 *Residual Stress*—Directional stress variations for magnetizable substrates may affect results. To verify results of the measurements, directional sensitivity should be determined and performance standards may be required for careful validation.

5.12 *Pressure of the Sensor against Surface under Examination*—Insulating coating thickness readings can be sensitive to the pressure exerted on the sensor pressed against the surface. See 8.5.6 on the allowed lift-off range.

5.13 *Temperature*—Eddy current measurements are generally affected by temperature variations of the material under examination. Coating porosity measurements may be particularly sensitive to temperature variations. Temperature corrections must account for both coating and substrate conductivity variations with temperature.

5.14 *Cleanness of Sensor Face and Examination Surface*—Measurements may be sensitive to foreign material that prevents intimate contact between sensor and coating surface. Metallic-coating property measurements should not be significantly affected unless the foreign material is conductive or magnetizable. Nonconducting coating thickness measurements are directly affected by lift-off variations caused by such foreign material.

5.15 *Models for Sensor Response*—The models for the sensor response used in the examination may not be appropriate for a specific application if they do not match the ~~sensor and excitation frequency.~~ sensor, the excitation frequency, and the nominal properties of the material being examined, such as a discrete coating on a nonmagnetic substrate. A database of responses may not be appropriate if the property ranges (for example, substrate conductivity, coating conductivity, coating thickness, and lift-off) spanned by the database are too small so that the data fall outside the database, if the database is sparse so that there are excessively large increments in the property values, or if the sensor response does not vary smoothly with the property values. The appropriateness of the sensor model can be validated by an air standardization with performance verification on an uncoated part having properties similar to the parts to be examined and by a performance verification on a coated part that has coating properties similar to the parts to be examined. Validation of the models for the sensor response must be documented if the models are not provided by the manufacturer of the instrument.

6. Basis of Application

6.1 The following items are subject to contractual agreement between the parties using or referencing this ~~standard.~~practice.

6.2 *Personnel Qualification:*

6.2.1 If specified in the contractual agreement, personnel performing examinations to this ~~standard~~practice shall be qualified in accordance with a nationally or internationally recognized NDT personnel qualification practice or 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 or standard used and its applicable revision shall be identified in the contractual agreement between the using parties.

6.3 *Qualification of Nondestructive Testing Agencies*—If specified in the contractual agreement, NDT agencies shall be qualified and evaluated as specified in ~~Practice~~Specification E543. The applicable edition of ~~Practice~~Specification E543 shall be specified in the contractual agreement.

6.4 *Procedures and Techniques*—The procedures and techniques to be utilized shall be as specified in the contractual agreement.

6.5 *Surface Preparation*—The pre-examination surface preparation criteria shall be in accordance with 5.13 and requirements specified in the contractual agreement.

6.6 *Timing of Examination*—The timing of examination shall be in accordance with the applicable contractual agreement.

6.7 *Extent of Examination*—The extent of examination shall be in accordance with the applicable contractual agreement.

6.8 *Reporting Criteria/Acceptance Criteria*—Reporting criteria for the examination results shall be in accordance with Section 9 unless otherwise specified. Since acceptance criteria are not specified in this ~~standard,~~practice, they shall be specified in the contractual agreement.

6.9 *Examination of Repaired/Reworked Items*—Requirements for examination of repaired/reworked items are not addressed in this ~~standard~~practice and if required shall be specified in the contractual agreement.

7. Calibration and Standardization

7.1 The instrument should be assembled, turned-on, and allowed sufficient time to stabilize in accordance with the manufacturer's instructions before use. The instrument should be standardized in air ~~and/or~~or on a reference ~~substrate~~ substrate, or both, as required by the measurement procedure (see Appendix X2). Standardization should be repeated at intervals established based on experience for a given application, including performance verification (see 7.3). Initially, standardization may need to be performed every 5 to 10 ~~minutes.~~min. Attention should be given to Section 5 and Section 8.

7.2 Air standardization involves measuring the sensor impedance in air, at least one spatial wavelength away from any conductive or magnetic objects, and adjusting the impedance to match a model response for the sensor. A measurement of the response with shunt sensor, which has the sensing element shorted, can also be used so that both the air response and the shunt response are used in the standardization. Performance verification on an uncoated part is recommended. This uncoated part should have properties that do not vary significantly with depth from the surface and is preferably a substrate reference part. The performance verification may involve measurements at a single lift-off, but measuring an electrical property, such as the electrical conductivity or magnetic permeability, as the lift-off is varied is recommended; the electrical property should have an approximately constant value over the lift-off range of interest for the application.

7.3 Reference parts with coatings are not required for standardization of conformable eddy current sensors that use models for the sensor ~~response,~~response since standardization can be successfully performed on substrate reference parts. However, performance verification on coated parts with known coating properties may be required, particularly when models do not accurately represent the coating system properties. A substrate reference part could be a flat coating-free specimen made from the material representative of the substrate with properties that do not vary significantly with depth from the surface. Substrate reference parts should match actual substrate properties as close as possible preferably accounting for thermal history of actual parts to avoid errors in coating property estimates. Reference substrate standardization can be performed on a uniform area of the substrate or a specimen made from material similar to the substrate. To validate the standardization, an uncoated part performance verification should be performed on the same area as the reference substrate where the standardization was performed. Insulating shims may be used to vary lift-off by a known amount and verify that the measured lift-off change corresponds to the thickness of the shim and that the measured electrical conductivity is not affected by the change in the lift-off and frequency.

7.4 Detailed performance verification on coated parts should be completed for new coating systems. If the models for the sensor response assume a single layer coating (for example, do not model an interdiffusion ~~zone)~~zone), then performance verification will verify the validity of the model ~~or~~for the sample set. This should be performed once on a significant set of samples prior to fielding a solution, but does not need to be performed in the field. However, field performance checks on one or two coating specimens are advisable. For example, a performance check on two samples with known thickness can be used to validate performance and ensure examination quality and reliability.

7.5 Instrument calibration should be performed in accordance with manufacturer's instructions. A permissible instrument calibration is an air standardization with extensive and documented performance verification measurements per manufacturer's instructions.

8. Procedure

8.1 Operate the instrument in accordance with the manufacturer's instructions giving appropriate attention to factors listed in Section 5.

8.2 Set the instrument to operate at multiple frequencies spanning a frequency range over which the instrument performance has been verified on coating specimens similar to the coating under examination. If the coating under examination is not similar to previously verified coatings, a performance verification should be performed on representative coating samples to establish the appropriate frequency range.

8.3 Perform air standardization ~~and/or~~or reference substrate standardization (see Appendix X2~~)~~), or both, as specified in Section 7. The operation of the instrument shall be validated by a performance verification on an uncoated material and, preferably, on a coated reference sample. Daily performance verification can be limited to on uncoated reference part and one to two coated reference parts. The need for performance verification measurements on uniform certified reference standards, including relevant NIST traceable standards as well as optional coated part performance verification, should be determined by the parties using this ~~standard.~~practice.

8.4 Perform measurements on the component at locations of interest. At the conclusion of the measurements, an additional performance verification on an uncoated or coated part is recommended to confirm measurement validity.

8.5 Observe the following precautions:

8.5.1 *Edge Effects*—The footprint of the conformable sensor should not go over an edge, hole, inside corner, etc., of a specimen unless an edge correction has been developed and validity of such a measurement has been demonstrated. For a conformable eddy current sensor, the distance from the edge of a part to the edge of the sensor footprint should be greater than half of the spatial wavelength, unless a procedure accounting for edge effects is available.

8.5.2 *Accounting for Variability*—Because of normal measurement variability due to probe/sensor setup and procedure application variations, it is useful to make several pick-and-place readings at each position. Local variations in coating thickness may also require that a number of measurements be made in any given area; this applies particularly to a rough surface.

8.5.3 *Directionality of Base-Metal Properties*—If the substrate is characterized by significant anisotropy such that it may have a pronounced effect on the reading, make the measurement on the specimen or part with the probe in the same orientation (relative to a dominant material processing direction associated with rolling or solidification) as that used during standardization.

8.5.4 *Residual Magnetism*—In some cases, it may be necessary to demagnetize the specimen or part to get valid results.