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Standard Guide for Eddy Current Testing of Electrically Conducting Materials Using Conformable Sensor Arrays[1]

This standard is issued under the fixed designation E2884; 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 guide covers the use of conformable eddy current sensor arrays for nondestructive examination of electrically conducting materials for discontinuities and material quality. The discontinuities include surface breaking and subsurface cracks and pitting as well as near-surface and hidden-surface material loss. The material quality includes coating or layer thickness, electrical conductivity, magnetic permeability, surface roughness, and other properties that vary with the electrical conductivity or magnetic permeability.

1.2 This guide is intended for use on nonmagnetic and magnetic metals as well as composite materials with an electrically conducting component, such as reinforced carbon-carbon composite or polymer matrix composites with carbon fibers.

1.3 This guide applies to planar as well as non-planar materials with and without insulating coating layers.

1.4 *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.

1.5 *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.*

1.6 *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]

E543 Specification for Agencies Performing Nondestructive Testing

E1316 Terminology for Nondestructive Examinations

~~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~~

[1] This guide 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**

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2.3 *AIA Standard:*[4]

NAS 410 Certification and Qualification of Nondestructive Testing Personnel

2.4 *Department of Defense Handbook:*

MIL-HDBK-1823A Nondestructive Evaluation System Reliability Assessment

2.5 *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 guide refer to Terminology E1316.

3.1 *Definitions of Terms Specific to This Standard:Definitions:* For definitions of terms relating to this guide, refer to Terminology E1316, including Section C on Electromagnetic Testing.

3.1.1 *B-Scan—B-Scan, n—*a method of data presentation utilizing a horizontal base line that indicates distance along the surface of a material and a vertical deflection that represents a measurement response for the material being examined.

3.1.2 *C-Scan—C-Scan, n—*a method of data presentation which provides measurement responses for the material being examined in two-dimensions over the surface of the material.

3.2.3 *conformable*—refers to an ability of sensors or sensor arrays to conform to non-planar surfaces without significant effects on the measurement results, or with effects that are limited to a quantifiable bound.

3.2.4 *depth of sensitivity*—depth to which the sensor response to features or properties of interest exceeds a noise threshold.

3.2.4.1 *Discussion*—

The depth of sensitivity can be larger or smaller than the depth of penetration since it incorporates a comparison between the signal obtained from a feature as well as measurement noise, whereas the depth of penetration refers to the decrease in field intensity with distance away from a test coil.

3.1.3 *discontinuity-containing reference standard—standard, n—*a region of the material under examination or a material having electromagnetic properties similar to the material under examination for which a discontinuity having known characteristics is present.

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3.1.4 *discontinuity-free reference standard—standard, n—*a region of the material under examination or a material having electromagnetic properties similar to the material under examination for which no discontinuities are present.

3.2.7 *drive winding*—a conductor pattern or coil that produces a magnetic field that couples to the material being examined.

3.2.7.1 *Discussion*—

The drive winding can have various geometries, including: 1) a simple linear conductor that is placed adjacent to a one-dimensional array of sensing elements; 2) one or multiple conducting loops driven to create a complex field pattern; and 3) multiple conducting loops with a separate loop for each sensing element.

3.2.8 *insulating shims*—conformable and substantially non-conducting or insulating foils that are used to measure effects of small lift-off excursions on sensor response.

3.2.9 *lift off*—normal distance from the plane of the conformable sensor winding conductors to the surface of the conducting material under examination.

3.2.10 *model for sensor response*—a relation between the response of the sensor (for example, impedance magnitude and phase or real and imaginary parts) and properties of interest (for example, electrical conductivity, magnetic permeability, lift-off, and material thickness) for at least one sensing element and at least one drive winding.

3.2.10.1 *Discussion*—

These model responses may be obtained from database tables and may be analysis-based or empirical.

3.1.5 *sensing element—element, n—*a means for measuring the magnetic field intensity or rate of change of magnetic field intensity, such as an inductive coil or a solid-state device.

3.1.5.1 *Discussion—*
The sensing elements can be arranged in one or two-dimensional arrays. They can provide either an absolute signal related to the magnetic field in the vicinity of the sense element or a differential signal.

~~3.2.12 *spatial half-wavelength*—spacing between the conductors of a linear drive winding with current flow in opposite directions.~~
~~3.2.12.1 *Discussion—*~~
~~This spacing affects the depth of sensitivity. The spatial wavelength equals two times this spacing. For a circular drive winding, the effective spatial half-wavelength is equal to the drive winding diameter.~~

~~3.2.13 *system performance verification*—the use of a measurement of one or more response values, typically physical property values, for a reference part to confirm that the response values are within specified tolerances to validate the system standardization and verify proper instrument operation.~~

4. Summary of Guide

4.1 The examination is performed by scanning a conformable eddy current sensor array over the surface of the material of interest, with the sensor array energized with alternating current of one or more frequencies. The electrical response from each sensing element of the eddy current sensor array is modified by the proximity and local condition of the material being examined. The extent of this modification is determined by the distance between the eddy current sensor array and the material being examined, as well as the dimensions and electrical properties (electrical conductivity and magnetic permeability) of the material. The presence of metallurgical or mechanical discontinuities in the material ~~alters the~~ and the presence of geometric changes in the material, such as coating thickness, layer thickness, or gap thickness between layers, alter the measured impedance of the eddy current sense elements. While scanning over the material, the position at each measurement location should be recorded along with the response of each sensing element in the sensor array. The measured responses and location information can then be used, typically in the form of a displayed image (C-scan (~~3.2.2~~3.1.2)) or in the form of a plot (B-scan (~~3.2.1~~3.1.1)), to determine the presence and characteristics of material property variations or discontinuities.

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4.2 The eddy current sensor arrays used for the examination are flexible and, with a suitable backing layer, can conform to both flat and curved surfaces, including fillets, cylindrical surfaces, etc. The sensor array can have a variety of configurations. These include: ~~1)~~*(1)* a linear drive conductor that is energized by the instrument alternating current and a linear array of absolute sense elements positioned parallel to the drive conductor; ~~2)~~*(2)* a complex drive conductor that produces a desired field pattern at each sensing element; and ~~3)~~*(3)* individual drive conductors associated with each sensing element. Associated with each sense element are one or more measurement responses that reflect the local material condition at each location over the surface. The sensor arrays may be used with models for the sensor response and appropriate algorithms to convert measured responses for each sensing element into physical properties, such as lift-off, electrical conductivity, magnetic permeability, coating thickness, ~~and/or substrate thickness.~~ or substrate thickness, or a combination thereof. Baseline values for these measurement responses or physical properties are used to ensure proper operation during the examination while local variations in one or more of these properties can be used to detect and characterize the discontinuity. For example, although, an impedance magnitude or other sensing element response can be used without a model to determine the presence of a flaw, a measurement of the lift-off at each sensing element location ensures that the sensor is conforming properly to the surface. Also, a position measurement capability, such as a rolling position encoder, can be used to measure location in the scan direction and ensure that sufficient data resolution is achieved. Visual or audio signaling devices may be used to indicate the position of the discontinuity.

5. Significance and Use

5.1 Eddy current methods are used for nondestructively locating and characterizing discontinuities and geometric property variations in magnetic or nonmagnetic electrically conducting materials. Conformable eddy current sensor arrays permit examination of planar and non-planar materials but usually require suitable fixtures to hold the sensor array near the surface of the material of interest, such as a layer of foam behind the sensor array along with a rigid support structure.

5.2 In operation, the sensor arrays are standardized with measurements in air ~~and/or~~or a reference ~~part.~~ part, or both. Responses measured from the sensor array may be converted into physical property values, such as lift-off, electrical conductivity, ~~and/or magnetic permeability.~~ or magnetic permeability, or a combination thereof. Proper instrument operation is verified by ensuring that these measurement responses or property values are within a prescribed range. Performance verification ~~on reference standards with known discontinuities is performed periodically.~~is performed periodically. Performance verification on a discontinuity-free reference standard or regions of the material being examined that do not contain discontinuities ensures that the electrical and geometric properties, such as electrical conductivity, layer thickness, or lift-off, or a combination thereof, are appropriate for the sensor array. Performance verification on a discontinuity-containing reference standard ensures that the sensor array response to the discontinuity is appropriate.

5.3 The sensor array dimensions, including the size and number of sense elements, and the operating frequency are selected based on the type of examination being performed. The depth of penetration of eddy currents into the material under examination depends upon the frequency of the signal, the electrical conductivity and magnetic permeability of the material, and some dimensions of the sensor array. The depth of penetration is equal to the conventional skin depth at high frequencies but is also related to the sensor array dimensions at low frequencies, such as the size of the drive winding and the gap distance between the drive winding and sense element array. For surface-breaking discontinuities on the surface adjacent to the sensor array, high frequencies should be used where the penetration depth is less than the thickness of the material under examination. For subsurface discontinuities or wall thickness measurements, lower frequencies and larger sensor dimensions should be used so that the depth of penetration is comparable to the material thickness.

5.4 Insulating layers or coatings may be present between the sensor array and the surface of the electrically conducting material under examination. The sensitivity of a measurement to a discontinuity generally decreases as the coating thickness ~~and/or lift-off~~ or lift-off, or both, increases. For eddy current sensor arrays having a linear drive conductor and a linear array of sense elements, the spacing between the drive conductor and the array of sense elements should be smaller than or comparable to the thickness of the insulating coating. For other array formats the depth of sensitivity should be verified empirically.

5.5 Models for the sensor response may be used to convert responses measured from the sensor array into physical property values, such as lift-off, electrical conductivity, magnetic permeability, coating thickness, ~~and/or substrate thickness.~~ or substrate thickness, or a combination thereof. For determining two property values, one operational frequency can be used. For nonmagnetic materials and examination for crack-like discontinuities, the lift-off and electrical conductivity should be determined. For magnetic materials, when the electrical conductivity can be measured or assumed constant, then the lift-off and magnetic permeability should be determined. The thickness can only be determined if a sufficiently low excitation frequency is used where the depth of sensitivity is greater than the material thickness of interest. For determining more than two property values, measurements at operating conditions having at least two depths of penetration should be used; these different depths of penetration can be achieved by using multiple operational frequencies or multiple spatial wavelengths.

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5.6 Processing of the measurement response or property value data may be performed to highlight the presence of discontinuities, to reduce background noise, and to characterize detected discontinuities. As an example, a correlation filter can be applied in which a reference signature response for a discontinuity is compared to the measured responses for each sensor array element to highlight discontinuity-like defects. Care must be taken to properly account for the effect of interferences such as edges and coatings on such signatures.

5.7 The measurement and analysis methods described in this guide can also be applied to applications where the sensor array is mounted against a surface or embedded within the material being examined. In that situation the sensor array response is monitored over a period of time instead of the scanning the sensor array over a specific location. This leads to the horizontal axes for the B-scans and C-scans to correspond to time or some other input associated with the test such as the number of loading cycles.

6. Basis of Application

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

6.2 *Personnel Qualification*—If specified in the contractual agreement, personnel performing examinations to this ~~standard~~guide should 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 should 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 should be qualified and evaluated as specified in Specification E543. The applicable edition of Specification E543 should be specified in the contractual agreement.

7. Interferences

7.1 *Base Material Property Variations*—Local variations in the magnetic permeability and electrical conductivity of the material under examination, possibly due to microstructural variations, can contribute to measurement noise that limits the capability of detecting small discontinuities. Shape filtering to candidate signature responses can help to reduce this effect. This also includes the presence and size of surface breaking and subsurface discrete features such as welds, fasteners, and cooling holes.

7.2 *Base Material Thickness*—The thickness of the material under examination can affect the measurement if it is smaller than or comparable to the depth of sensitivity. If necessary, the thickness can be determined as a property value using the model for the sensor response.

7.3 *Residual Magnetism*—In magnetic materials, residual magnetism may affect the measurement and appear as a local response change. In some cases, it may be necessary to demagnetize the specimen or part to get valid results.

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

7.5 *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. System performance verification tests should be run to verify lift-off sensitivity using insulating shims.

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7.6 *Conductive Coatings*—The presence of electrically conductive coatings at the surface of the material under examination can influence the measurement response. A reference standardization performed with a nominal conductive coating thickness can help to account for the presence of this type of coating, but it will not necessarily account for conductive coating thickness variations over the material surface. Preferably, the models for the sensor response should account for the presence of this type of coating with a physical property that is determined, such as the coating thickness or coating electrical conductivity, or ~~both, a physical property that is determined.~~both.

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7.7 *Insulating Coatings*—The thickness of insulating coatings at the surface of the material under examination will affect the measurement response. The sensitivity to discrete features is generally reduced as the insulating coating thickness increases. If models for the sensor response are used, the models should account for the presence of this type of coating. Coating thickness variations over the material surface can be absorbed into the lift-off property value.

7.8 *Edge Effect*—Examination methods may be sensitive to abrupt surface changes near material edges. Therefore, measurements made too near an edge 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 should 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.

7.9 *Instrument Stability*—Drift and noise in the instrumentation can cause inaccuracies in the measurement. Restandardization and system performance verification should be performed whenever the baseline response values exceed the threshold range.

7.10 *Pressure of the Sensor Array against Surface under Examination*—Insulating coating thickness readings can be sensitive to the pressure used to hold the sensor array against the surface.

7.11 *Temperature*—Eddy current measurements are generally affected by temperature variations of the material under examination.

7.12 *Cleanness of Sensor Array Face and Examination Surface*—Measurements may be sensitive to foreign material and surface roughness that prevents intimate contact between the sensor array and the surface of the material under examination. Magnetic permeability ~~and/or~~or electrical conductivity property ~~values~~ values, or both, should not be significantly affected unless the foreign material is electrically conductive, magnetizable, or causes a rapid spatial variation in lift-off. Non-conducting coating thickness measurements are directly affected by lift-off variations caused by such foreign material, surface roughness, fretting scars and scratches.

7.13 *Models for Sensor Response*—The models for the sensor response, if used in the examination, may not be appropriate for a specific application if they do not match the sensor and excitation frequency. A database of responses may not be appropriate if the property ranges (for example, electrical conductivity 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 air standardization with system performance verification on a reference part or a discontinuity-free portion of the material being examined.

8. Apparatus

8.1 *Instrumentation*—The electronic instrumentation should be capable of energizing the eddy current sensor array with alternating current of one or more suitable frequencies and should be capable of measuring changes in the impedance of each element in the sensor array. Depending upon the instrumentation, the response for each sense element can be measured in parallel or a multiplexer can be used to switch between one or more of the sense elements. Typically, a multiplexer is used when the number of sense elements is greater than the number of data acquisition channels for impedance measurement. When a multiplexer is used, particularly for eddy current sensor arrays with multiple drive coils and multiple sense elements, it may be necessary to multiplex in a special pattern that avoids undesired coupling between the individual coils. The equipment may include a capability to convert the impedance information into physical property values for the material under examination, including the lift-off, at each point in the ~~C-scan~~ C-scan (~~3.2.2~~3.1.2) or B-scan (~~3.2.1~~3.1.1~~.~~).

8.2 *Eddy Current Sensor Array*—The eddy current sensor array should be capable of inducing currents in the material under examination and sensing changes in the physical characteristics of the material under examination. The geometry of the sensor array, including the number of sense elements, should be selected based on the application. Example configurations include:

8.2.1 A linear drive conductor and one or more linear arrays of absolute sense elements positioned parallel to the drive conductor, where the second linear array is aligned with the first row to add redundancy or offset to improve image resolution in the direction transverse to the scan direction,

8.2.2 A complex drive conductor that produces a desired field pattern at each sensing element, and

8.2.3 Individual drive conductors associated with each sensing element. The array can be in contact with the material being tested or offset by an intended lift-off distance (for non-contact scanning) with a support shaped approximately to match the surface being inspected.

9. Calibration and Standardization

9.1 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 or on a reference part, or both. Standardization should be repeated at intervals established based on experience for a given application, including performance verification. Depending upon the application, standardization may be required at each examination or more rarely such as once per week.

9.2 *Air Standardization*—Air standardization involves measuring the impedance of a sensor array with absolute sense elements in air, at least one spatial wavelength away from any conductive or magnetic objects, and adjusting the impedance for each sensing element to match a model for the sensor response. A measurement of the response with a 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. Measurements on electrically conductive materials after air standardization should provide absolute electromagnetic property (electrical conductivity or magnetic permeability, or both) and lift-off values. To validate the standardization, a baseline system performance verification should be performed.

9.3 *Reference Part Standardization*—Reference part standardization involves measuring the impedance of the sensor array proximate to a discontinuity-free reference standard for one or more known lift-offs and adjusting the impedance for each sensing element to match a pre-specified sensor response. This can be done with the sensor array stationary or moving. The adjustment may be used to remove offsets between a model for the sensor response and the measured responses for each sensing element.

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Insulating shims may be used to vary lift-off by a known amount. Reference part standardization may be performed in combination with air standardization. To validate the standardization, a baseline system performance verification should be performed.

9.3.1 The reference part should have electrical properties (electrical conductivity and magnetic permeability) and geometry (thickness and curvature) similar to the material to be examined. Preferably the reference part has the same material (for example, chemistry, microstructure, and heat treatment) and shape as the material under examination. The degree of similarity between the reference part and the material under examination depends upon the application. For example, for hidden material loss in a magnetic metal a flat reference block having a magnetic relative permeability within approximately ~~50 %~~ 50 % of the relative permeability of the material under examination could be sufficient. For crack detection in nonmagnetic electrically conducting materials, the reference part should have an electrical conductivity within about ~~25 %~~ 25 % of the electrical conductivity of the material under examination.

9.4 *System Performance Verification*—System performance verification refers to measurements on a reference part to confirm that the measured responses are within specified tolerances for the application. This serves to validate the standardization and verify proper instrument operation. System performance verification is a quality control procedure that does not represent standardization and should be documented in the report (see Section 11).

9.4.1 *Baseline System Performance Verification*—A baseline system performance verification uses measurements on a discontinuity-free reference standard to verify standardization of the instrument. Measurements are performed with the sensor array for one or more lift-offs to ensure that the measured responses or property values (for example, electrical conductivity for nonmagnetic materials or magnetic permeability for magnetic materials) are not significantly affected by the lift-off, and that the lift-off remains within an acceptable range. In addition to the measurements on the reference standard, the lift-off range should be verified at all locations on the material being examined that are far from discontinuities.

9.4.2 *Discontinuity System Performance Verification*—A discontinuity system performance verification uses measurements on a discontinuity-containing reference standard to verify instrument operation. The discontinuity-containing reference standard should contain one or more discontinuities that are representative of the discontinuities to be found in the examination. The response variation due to the discontinuity as well as the background variation associated with discontinuity-free regions of the reference standard are to be within specified tolerances. For example, for examining nonmagnetic materials for cracks, the lift-off response can be used to ensure that the sensor array is within an acceptable range for the examination while the electrical conductivity response can be used to indicate the presence and size of the crack. When possible, the discontinuity-containing reference standard should have the same shape as the part being examined.

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9.4.2.1 This performance verification can also entail multiple levels of verification. For example, basic system operation can be verified with the response from a single discontinuity being above a specified detection threshold. However, if the response due to the discontinuity of interest is near the detection threshold, then the response of a second discontinuity can also be used to verify that both signals are above the detection threshold and that the signal responses trend correctly with discontinuity size.

9.4.3 The reference standards for performance verification should have the same material (for example, chemistry, microstructure, and heat treatment) and shape as the material under examination. The discontinuity-free reference standard may be a distinct part or it can be a portion of the material being examined that is distant from any discontinuities. The discontinuity-containing reference standard may be a representative part with a known discontinuity, electric discharge machined (EDM) notch, or other machined feature.

9.5 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.

10. Procedure

10.1 Operate the instrument in accordance with the manufacturer's instructions.

10.2 Set the instrument to operate at one or more frequencies over which the instrument performance has been verified on materials or specimens similar to the material under examination.

10.3 Perform air standardization or reference part standardization, or both, as specified in Section 9 prior to examination or whenever improper functioning of the examination apparatus is suspected. The operation of the instrument should be validated by