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Non-magnetic metallic coatings on metallic and non-metallic basis materials — Measurement of coating thickness — Phase-sensitive eddy-current method

Revêtements métalliques non magnétiques sur des matériaux de base métalliques et non métalliques — Mesurage de l'épaisseur de revêtement — Méthode par courants de Foucault sensible aux variations de phase

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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ISO 21968 was prepared by Technical Committee ISO/TC 107, *Metallic and other inorganic coatings*, Subcommittee SC 2, *Test methods*.

Non-magnetic metallic coatings on metallic and non-metallic basis materials — Measurement of coating thickness — Phase-sensitive eddy-current method

1 Scope

This International Standard describes a method of using phase-sensitive eddy-current instruments for non-destructive measurements of the thickness of non-magnetic metallic coatings on metallic and non-metallic basis materials, such as:

a) zinc, cadmium, copper, tin or chromium on steel;

b) copper or silver on composite materials.

The phase-sensitive method can be applied without thickness errors to smaller surface areas and to stronger surface curvatures than the amplitude-sensitive eddy-current method described in ISO 2360[1], and is less affected by the magnetic properties of the basis material. However, the phase-sensitive method is more affected by the electrical properties of the coating materials.

When measuring metallic coatings on metallic basis materials, the product of conductivity and permeability (σ, μ) of one of the materials should be at least a factor of 1,5 times the product of conductivity and permeability for the other material. Non-ferromagnetic materials have a relative permeability of 1.

2 Principle

An eddy-current probe (or integrated probe/instrument) is placed on (or near) the surface of the coating(s) to be measured, and the thickness is read from the instrument's readout.

For each instrument, there is a maximum measurable thickness of the coating.

Since this thickness range depends on both the applied frequency of the probe system and the electrical properties of the coating, the maximum thickness should be determined experimentally, unless otherwise specified by the manufacturer.

An explanation of eddy-current generation and the calculation of the maximum measurable coating thickness, d_{max}, is given in Annex A.

However, in the absence of any other information, the maximum measurable coating thickness, d_{max}, can be estimated using Equation (1):

$$d_{max} = 0{,}8\delta_0 \tag{1}$$

where δ_0 is the standard penetration depth of the coating material [see Equation (A.1)].

3 Equipment

3.1 Probe, containing an eddy-current generator, and a **detector** linked to a system capable of measuring and displaying changes in amplitude and phase, normally as a direct readout of coating thickness.

NOTE 1 The probe and measuring system/display may be integrated into a single instrument.

NOTE 2 Factors affecting measurement accuracy are discussed in Clause 5.

4 Sampling

Sampling depends on the specific application and coating to be tested; the area, location and number of test specimens shall be agreed between interested parties and shall be included in the test report (see Clause 9).

5 Factors affecting measurement accuracy

5.1 Coating thickness

A measurement uncertainty is inherent in the method. For thin coatings, this measurement uncertainty (in absolute terms) is constant, independent of the coating thickness. The absolute value of the uncertainty depends on the applied frequency of the probe system, and also on the conductivity and permeability of the used sample materials. With increasing thickness within the measurement range of the probe system, this uncertainty becomes a function of the thickness and is approximately a constant fraction of that thickness.

The mean of several measurements should be used as the thickness value to reduce the uncertainty, especially in the lower part of the measurement range of the used probe system.

5.2 Electrical properties of the basis materials

Both conductivity and permeability have some effect on the measurement, but these effects are small when compared to those with the amplitude method described in ISO 2360[1].

5.3 Electrical properties of the coating materials

Coating thickness measurements are affected by the electrical conductivity of the coating material, which in turn can be dependent upon composition, the coating process (additives, contaminants, etc.) and any post-coating treatments, such as heating or mechanical working.

5.4 Basis-metal thickness

For each instrument, there is a critical minimum basis-metal thickness above which measurements will not be affected by an increase in thickness.

This thickness depends on both the applied frequency of the probe system and the electrical and magnetic properties of the basis material. Its value should be determined experimentally, unless otherwise specified by the manufacturer.

An explanation of eddy-current generation and the calculation of the minimum basis-material thickness, d_{min}, is given in Annex A.

However, in the absence of any other information, the required minimum thickness of basis material, d_{min}, can be calculated from Equation (2):

$$d_{\text{min}} = 2{,}5\delta_0 \qquad (2)$$

where δ_0 is the standard penetration depth of the metallic basis material [see Equation (A.1)].

5.5 Edge effects

Eddy-current instruments can be sensitive to abrupt changes in surface contour of the test specimen. Therefore, measurements made too near to an edge or corner may not be valid, unless the instrument has been specifically calibrated for such measurements (see 6.2.4 and Annex B).

NOTE The phase-sensitive eddy-current instruments can be substantially less affected by edge effects when compared with the amplitude method of ISO 2360.

5.6 Surface curvature

Measurements are affected by the curvature of the test specimen. This influence of curvature varies considerably with the make and type of instrument and probe, but always becomes more pronounced as the radius of curvature decreases. Measurements made on curved test specimens may not, therefore, be valid unless the instrument is specifically calibrated for the surface curvature in question, or a special probe, which compensates for surface influence, is used.

The effect of surface curvature can be reduced by the use of so-called microprobes, in which the radial area of probe influence has been reduced.

NOTE The phase-sensitive eddy-current measurement can be substantially less affected by the surface curvature of the test specimen when compared with the amplitude-sensitive eddy-current method given in ISO 2360.

5.7 Surface roughness

Measurements are influenced by the surface topography of the basis material and of the coating. Rough surfaces can cause both systematic and random errors. Random errors can be reduced by making multiple measurements, with each measurement being made at a different location, and then calculating the average value of this series of measurements.

If the basis material is rough, the zero of the instrument shall be checked at several locations on a typical sample of the uncoated, rough, basis material. If no typical uncoated basis material is available, the coating of the test specimen shall be stripped, at least over part of its area, with a chemical solution which does not attack the basis material.

NOTE The phase-sensitive eddy-current measurement can be substantially less affected by basis-material roughness and coating roughness when compared with the amplitude-sensitive eddy-current method given in ISO 2360.

5.8 Lift-off effect

If the probe is not placed directly down onto the coating, the gap between probe and coating (lift-off) will affect the measurement of the metal coating thickness. The use of an appropriate electronic circuit design, and/or mathematical algorithm in the instrument, allows lift-off compensation to be applied for gaps of up to 1 mm.

Lift-off compensation shall be verified in accordance with the manufacturer's instructions, by the use of electrically non-conductive shims of known thickness which are inserted between the probe and the coating.

Lift-off can be produced intentionally, as when measuring a metallic coating through paint, or when it is necessary to make a contactless measurement, or unintentionally due to the presence of foreign particles between the probe and coating.

The probe tip shall be frequently checked for cleanliness.

5.9 Probe pressure

The pressure with which the probe is applied to the test specimen can affect the instrument reading and shall be made constant.

NOTE The phase-sensitive eddy-current measurement can be substantially less affected by the pressure with which the probe is placed onto the sample when compared with the amplitude-sensitive eddy-current method given in ISO 2360. Contactless measurements are possible (see 5.8.).

5.10 Probe tilt

Unless otherwise instructed by the manufacturer, the probe should be applied perpendicularly to the coating surface, as tilting the probe away from the perpendicular can cause measurement errors.

The possibility of tilt inadvertently occurring can be minimized by probe design, or by the use of a probe-holding jig.

5.11 Temperature effects

Because temperature changes affect the characteristics of the probe, it should be used under approximately the same temperature conditions as those used for calibration, unless the probe has built-in temperature compensation.

Most metals change their electrical conductivity with temperature. Because the measured coating thickness is influenced by changes in the electrical conductivity of both coating and basis metals, large temperature changes should be avoided.

5.12 Intermediate coatings

The presence of an intermediate coating can affect the measurement of the coating thickness, if the electrical characteristics of that intermediate coating differ from that of the coating or basis material. If a difference does exist then the measurements will, in addition, be affected by an intermediate coating thickness of less than d_{min}. If the thickness is greater than d_{min} then the intermediate coating can be treated as the basis material.

It has been found that some instruments having probe systems operating with multiple frequencies may be able to measure both top and intermediate coatings.

6 Procedure

6.1 Calibration of instruments

6.1.1 General

Before use, each instrument shall be calibrated in accordance with the manufacturer's instructions, using suitable calibration standards. Particular attention shall be paid to the factors listed in Clause 5.

At the time of calibration, the instrument and the calibration standards shall be at a temperature close to the temperature of the items to be measured, in order to minimize conductivity changes due to temperature variations.

Calibration checks should also be carried out, as necessary, during the determinations to avoid instrument drift.

6.1.2 Calibration standards

Instrument calibration shall be made using at least two standards of different and known thicknesses. One of these standards can sometimes be of the uncoated basis material.

Such standards should have their thicknesses traceable to a certifiable source.

The electrical conductivity and magnetic permeability of both coating and basis materials should be identical to the corresponding properties of the parts to be measured.

As calibration standards are subject to wear and deterioration with time and use, they should be recalibrated and/or replaced periodically at time intervals established locally or after consultation with the manufacturer.

6.1.3 Verification

The electrical properties of the basis material of the calibration standards shall be similar to those of the basis material of the test specimen.

To confirm their suitability, the readings obtained with the basis material of the uncoated calibration standard, and with that of the test specimen, should be compared.

If the basis material thickness exceeds the critical thickness, as defined in 5.4, the thickness measurement is not affected by the thickness of the basis material.

If the critical thickness is not exceeded, the thickness of the basis material should be the same for the test and for the calibration. If, under practical conditions, this is not possible then it may be possible to back either the standard or the test specimen with a sufficient thickness of a material having similar electrical properties to make the readings independent of the basis-material thickness. If this method is used, tests should be made to confirm that it is acceptable and to establish the presence of any additional errors.

If the curvature of the coated surface to be measured is such as to preclude calibration on a flat surface, the standards used for calibration shall have the same radii of curvature as the specimen to be measured, unless a special probe compensating for the curvature influence is used.

6.2 Determination

6.2.1 General

Operate the instrument in accordance with the manufacturer's instructions, giving appropriate attention to the factors mentioned in Clause 5.

Check the calibration of the instrument, using valid calibration standards, at the test site, each time the instrument is put into service and at sufficient intervals during use as recommended by the manufacturer to ensure proper performance (see 6.1).

The precautions listed in 6.2.2 to 6.2.6 shall be observed.

6.2.2 Surface cleanliness

Before making measurements, remove any foreign matter, such as dirt, oil, grease and corrosion products, from the surface of standards and test specimens, without removing any coating material.

6.2.3 Basis-metal thickness

Check that the basis-material thickness exceeds the critical thickness (see 5.4). If not, either use the back-up method described in 6.1.3 or ensure that the calibration was carried out on a calibration standard having the same thickness and electrical properties as the test specimen.

6.2.4 Edge effects

Do not make measurements close to an edge, hole, inside corner, etc., of a test specimen unless the validity of the calibration for such measurements has been demonstrated (see Annex B).

6.2.5 Curvature

Do not make measurements on a curved surface of a test specimen, unless the validity of the calibration for such measurements has been demonstrated.

6.2.6 Number of readings

A number of measurements made on the same spot, if necessary using a probe jig, will provide information on the repeatability (standard deviation) of the instrument and its probe at that time and at the thickness being measured (see note).

NOTE A coefficient of variation, V, can be calculated from this standard deviation. V corresponds to the relative standard deviation (e.g. in percent) and allows a direct comparison of the standard deviation for different thicknesses.

A number of measurements, made by moving the probe between each measurement, and within a specified area on the coated surface, will provide information on the repeatability of the instrument and the thickness variation of the coating within that specified area.

If a coating surface is rough or if the test specimens are known to have large thickness gradients across their surfaces (e.g. because of size and/or shape), the origins of measurement variations should be established by multiple measurements.

7 Expression of results

The expression and presentation of results shall be agreed between the interested parties and normally include:

— a list of all the readings taken;

— the mean, maximum and minimum readings;

— the standard deviation and/or coefficient of variation.

8 Measurement uncertainty

The instrument, its calibration, and its operation shall be such that the coating thickness can be determined to within 10 % of its true thickness.

9 Test report

The test report shall include the following information:

a) all information necessary for the identification of the test specimen;

b) a reference to this International Standard, including its year of publication, i.e. ISO 21986:2005;

c) the sizes of the test areas over which the measurements were made, in square millimetres (mm^2);

NOTE Other units of measurement may be used, with agreement between the supplier and client.

d) the location(s) of the test area(s) on each specimen;

e) the number of test specimens measured;

f) an identification of the instrument, probe and standards used for the tests, including reference to any validation certification of the equipment;

g) the results of the test, reported as the measured thicknesses, in micrometres, at each area at which the tests were carried out, including the results of the individual determinations and their mean for each reported measurement;

h) the name of the operator and testing laboratory;

i) any unusual features observed and any circumstances or conditions thought likely to affect the results or their validity;

j) any deviation from the procedure specified;

k) any unusual features (anomalies) observed during the test;

l) the date of the test.

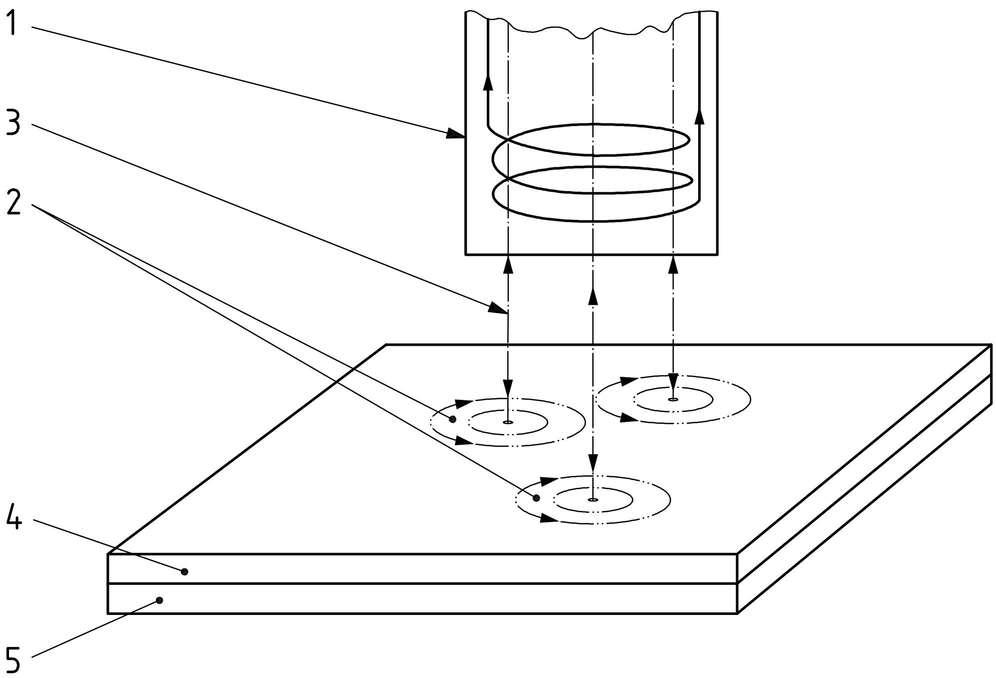
Annex A
(informative)

Eddy-current generation in a metallic conductor

Eddy-current instruments work on the principle that a high-frequency electromagnetic field generated in the probe system of the instrument will produce eddy currents in an electrical conductor on which the probe is placed.

These currents result in a change of the amplitude and phase of the probe-coil impedance, which can be used as a measure of the thickness of the metallic coating.

Figure A.1 represents eddy-current generation in a metal conductor.



Key

1 probe (containing eddy-current generator)

2 eddy-currents set up in the metal conductor by the magnetic field

3 oscillating electromagnetic field generated by the probe

4 coating (item being measured)

5 basis material

Figure A.1 — Schematic representation of eddy-current generation in a metal conductor

The eddy-current density, $J(\delta)$, changes its magnitude with increasing distance from the surface of the conductor. At the depth δ_0 (standard penetration depth), the electromagnetic field and consequently the current density, $J(\delta_0)$, drops to 37 % of the current density, $J(0)$, at the surface, i.e. $\frac{J(\delta_0)}{J(0)} = \frac{1}{e}$.

The standard penetration depth, δ_0, is a useful value for some important rough estimations. It may be calculated, in millimetres, using Equation (A.1):

$$\delta_0 = \frac{503}{\sqrt{f \cdot \sigma \cdot \mu_r}} \tag{A.1}$$

where

f is the probe operating frequency, in hertz (Hz);

σ is the electrical conductivity of the conductor, in megasiemens per metre (MS/m);

μ_r is the relative permeability of the conductor (for non-magnetic materials, $\mu_r = 1$).

The maximum measurable thickness of the conductive coating is limited by the standard penetration depth, δ_0, i.e. the measurement range is limited by the probe frequency as well as by the conductivity of the coating of interest. The approximate maximum measurable thickness, d_{max}, in millimetres, may be estimated from Equation (A.2):

$$d_{max} = 0{,}8\delta_0 \tag{A.2}$$

A further increase of the coating thickness may result in an undetectable increase of the eddy-current density.

If the metallic coating is placed on a metallic basis material, it has to be ensured that the measurement result is not affected by variations in the eddy-current density created in the basis material because of varying thickness of the basis material. This minimum thickness, d_{min}, in millimetres, can be estimated from Equation (A.3) (see 5.4.):

$$d_{min} = 2{,}5\delta_0 \tag{A.3}$$

Therefore, the minimum basis-material thickness is determined by the standard penetration depth, δ_0, i.e. d_{min} is determined by the probe frequency, as well as by the conductivity and the permeability of the basis material.

The amplitude-sensitive eddy-current method is best suited to the measurement of non-conductive coatings on non-magnetic basis metals but also to bare non-magnetic metallic coatings on non-conductive basis materials (see ISO 2360). The phase-sensitive eddy-current method described in this International Standard is best suited to the measurement of non-magnetic metallic coatings on metallic or non-metallic basis materials, especially if the metallic coating has to be measured through a paint or a contactless measurement is necessary, i.e. a lift-off compensation is necessary.

Annex B
(normative)

Test for edge effect

A simple edge-effect test, to assess the effect of the proximity of an edge, consists in using a clean uncoated sample of the basis metal as follows. The procedure is illustrated in Figure B.1.

Step 1

Place the probe on the sample, well away from the edge.

Step 2

Adjust the instrument to read zero.

Step 3

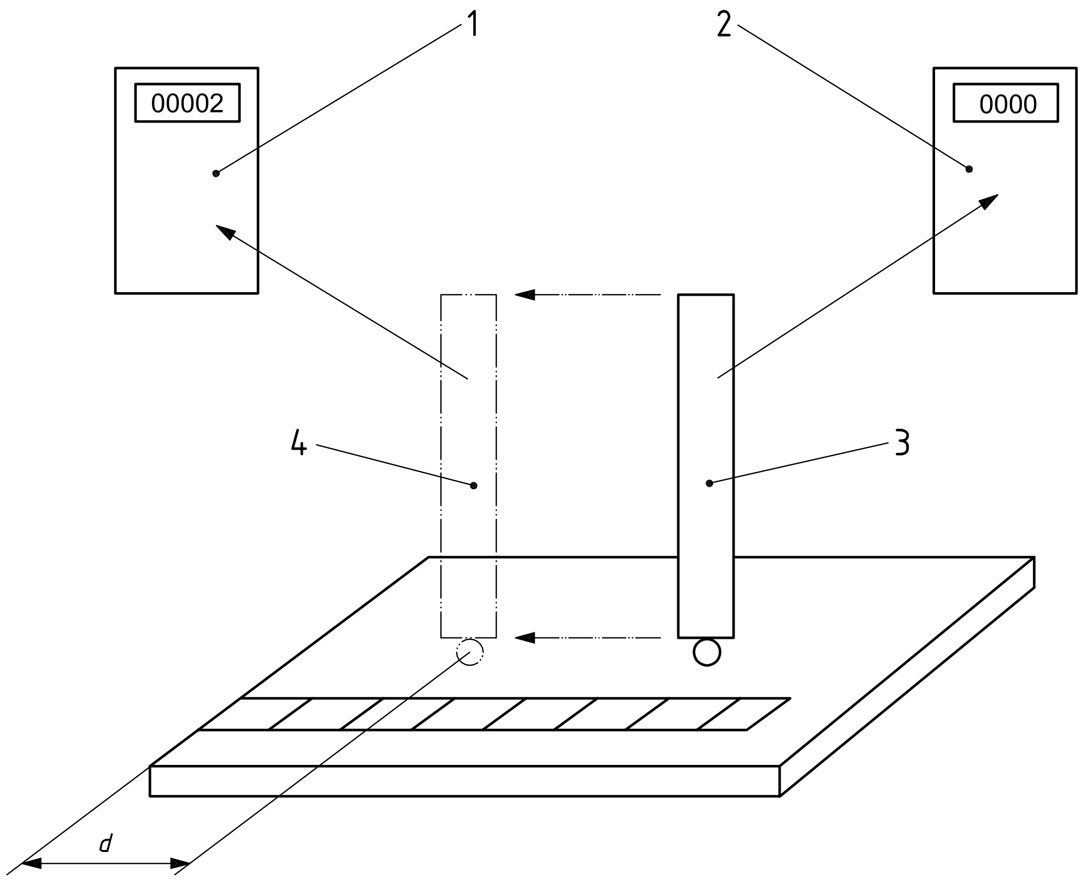
Progressively, bring the probe towards the edge and note where a change of the instrument reading occurs with respect to the expected uncertainty or to the given thickness.

Step 4

Measure the distance, d, from the probe to the edge (see Figure B.1).

The instrument may be used without correction, provided that the probe is further from the edge than the distance measured, as indicated above. If the probe is used closer to the edge, a special calibration correction is required. If necessary, refer to the manufacturer's instructions.

If the sample to be measured is not flat, then an uncoated sample that is representative both in size and shape shall be used.



Key

1 meter showing final reading

2 meter in start position

3 probe in start position

4 probe in finish position

d distance from the probe to the edge

Figure B.1 — Schematic representation of the test for edge effect

Bibliography

[1] ISO 2360, *Non-conductive coatings on non-magnetic electrically conductive basis materials — Measurement of coating thickness — Amplitude-sensitive eddy-current method*

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