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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

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/107, *Metallic and other inorganic coatings*.

This second edition cancels and replaces the first edition (ISO 21968:2005), which has been technically revised. The main changes compared with the previous edition are as follows:

— this document has been adapted to the current requirements of ISO/IEC Guide 98-3 (also known as “GUM:1995”);

— hints, practical examples and simple estimations of the measurement uncertainty for most important factors have been added;

— repeatability and reproducibility values for typical applications of the method have been added;

— the annex has been expanded with further applications and experimental estimations of factors affecting the accuracy.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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

1 Scope

This document specifies a method for 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 specified in ISO 2360, 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.

In this document, the term “coating” is used for materials such as, for example, paints and varnishes, electroplated coatings, enamel coatings, plastic coatings, claddings and powder coatings.

This method is particularly applicable to measurements of the thickness of metallic coatings. These coatings can be non-magnetic metallic coatings on non-conductive, conductive or magnetic base materials, but also magnetic coatings on non-conductive or conductive base materials.

The measurement of metallic coatings on metallic basis material works only when the product of conductivity and permeability (σ, μ) of one of the materials is at least a factor of two times the product of conductivity and permeability for the other material. Non-ferromagnetic materials have a relative permeability of one.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2064, *Metallic and other inorganic coatings — Definitions and conventions concerning the measurement of thickness*

ISO 4618, *Paints and varnishes — Terms and definitions*

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2064, ISO 4618 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
adjustment of a measuring system
set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity to be measured

Note 1 to entry: Types of adjustment of a measuring system can include zero adjustment of a measuring system, offset adjustment, and span adjustment (sometimes called gain adjustment).

Note 2 to entry: Adjustment of a measuring system should not be confused with *calibration* (3.2), which is a prerequisite for adjustment.

Note 3 to entry: After an adjustment of a measuring system, the measuring system shall usually be recalibrated.

Note 4 to entry: Colloquially the term "calibration" is frequently, but falsely, used instead of the term "adjustment". In the same way, the terms "verification" and "checking" are often used instead of the correct term "calibration".

[SOURCE: ISO/IEC Guide 99:2007, 3.11 (also known as "VIM"), modified — Note 4 to entry has been added.]

3.2
calibration
operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication

Note 1 to entry: A calibration may be expressed by a statement, calibration function, calibration diagram, calibration curve, or calibration table. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty.

Note 2 to entry: Calibration should not be confused with *adjustment of a measuring system* (3.1), often mistakenly called "self-calibration", nor with verification of calibration.

Note 3 to entry: Often, the first step alone in the above definition is perceived as being calibration.

[SOURCE: ISO/IEC Guide 99:2007, 2.39 (also known as "VIM")]

4 Principle of measurement

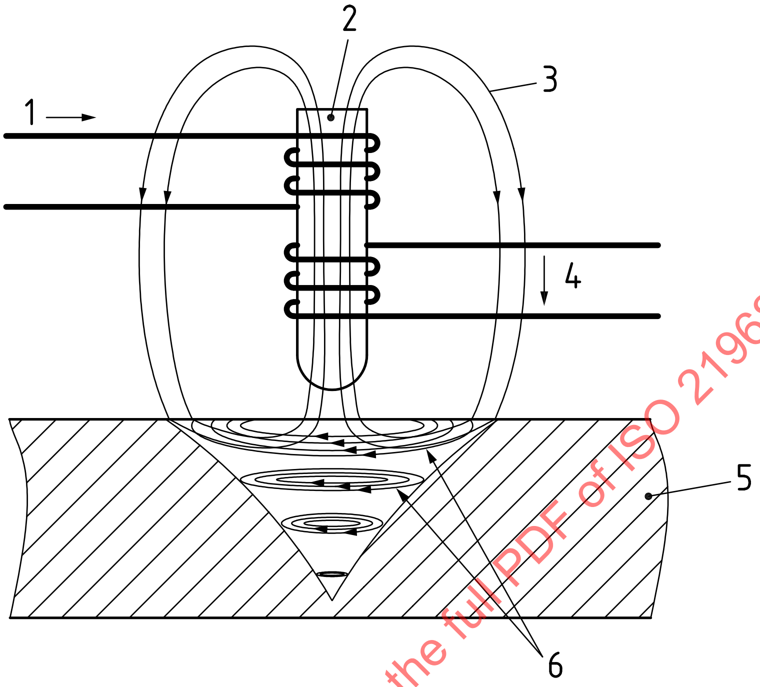
Phase-sensitive eddy-current instruments work on the principle that a high-frequency electromagnetic field generated by the probe system of the instrument will produce eddy currents in the coating on which the probe is placed and in the base material beneath the coating in case this base material is conductive (see Figure 1). These induced currents cause a change of the electromagnetic field surrounding the probe coil system and therefore result in a change of the amplitude and the phase angle of the probe coil impedance. The induced eddy-current density is a function of the coating thickness, the conductivity of the coating material, the used frequency of the probe system and the base metal conductivity. If the thickness of a coating of constant conductivity is increased for a given frequency, the impedance vector describes a so-called local function of the thickness in the impedance plane (see Figure 2). Each point of this local curve connects a phase angle of the impedance vector with the respective coating thickness. Consequently, this impedance angle (phase shift) can be used as a measure of the thickness of the coating on the conductor by means of a calibration with reference standards (see also Annex A).

In order to measure a change of the coil impedance phase angle, the test coil is usually part of a coil system and is coupled with the exciting coil on one ferrite core such as in a transformer (see Figure 1). The changes of phase angle and amplitude due to the impact of the induced eddy currents can be measured, for example, using a lock in amplifier. These values are usually pre-processed by digital means and the resulting thickness is then calculated and displayed.

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

NOTE 1 Annex C describes the basic performance requirements of the equipment.

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



Key

1 exciting current

2 ferrit core of probe

3 high-frequency alternating magnetic field

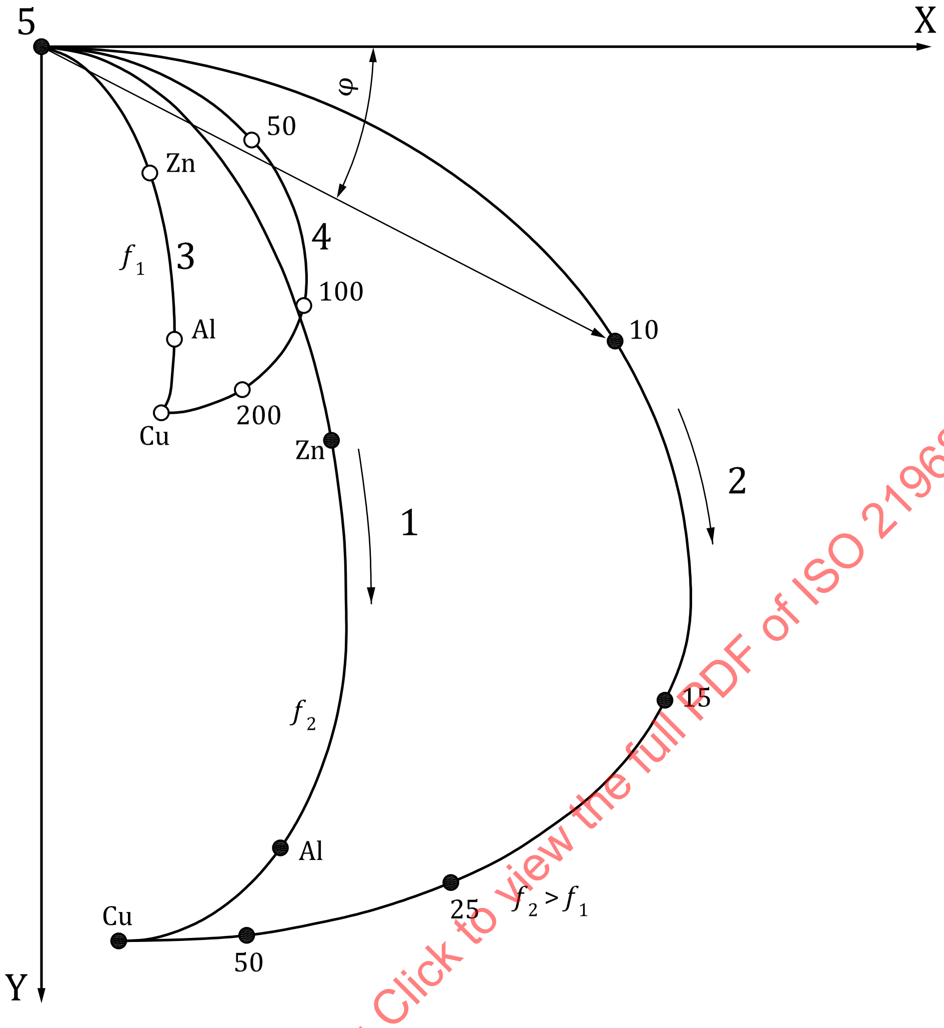
4 measured signal $U = f(t(\varphi))$

5 base material (conductive)

6 induced eddy currents

Figure 1 — Phase-sensitive eddy-current method

Dimensions in micrometre



Key

1 conductivity local curve for the frequency f_2
2 thickness local curve of Cu for the frequency f_2
3 conductivity local curve for the frequency f_1
4 thickness local curve of Cu for the frequency f_1
5 coil in air (unaffected)
X real part
Y imaginary part

Figure 2 — Thickness local curves of Cu in the normalized impedance plane for two frequencies f_1 and f_2

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 conductivity 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, t_{max}, is given in Annex A.

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

$$t_{max} \approx 0{,}8 \cdot \delta_0 \quad (1)$$

where δ_0 is the standard penetration depth of the coating material (see Annex A).

5 Factors affecting measurement uncertainty

5.1 Basic influence of the coating thickness

The sensitivity of a probe, i.e. the measurement effect, depends on the used frequency, the conductivity of the coating and the base material, and the properties of the probe system. Besides the properties of the probe system, the resulting uncertainty of the thickness also depends on the sample materials, such as the homogeneity of the coating and base metal conductivity and roughness.

5.2 Electrical properties of the coating

The conductivity of the coating as well as the base material determine the induced eddy-current density for a given probe system and frequency. Consequently, the coating and base metal conductivity cause the measurement effect for this method. The relationship between coating thickness and the measured value depends strongly on the conductivity of both the coating and base material. Therefore, calibration procedures and measurements shall be made on the same material. Different materials with different conductivities as well as local fluctuations of the conductivity or variations between different samples can cause (more or less) errors in the thickness reading.

5.3 Geometry — Base material thickness

In cases of a conductive base material (base metal), the generation of eddy currents by the coil's magnetic field in the depth of the base metal is obstructed if the base metal thickness is too small. This influence can only be neglected above a certain critical minimum base metal thickness.

Therefore, the thickness of the base metal should always be higher than this critical minimum base metal thickness. An adjustment of the instrument can compensate for errors caused by thin base metal. However, any variation in thickness of the base metal can cause increased uncertainty and errors.

The critical minimum base metal thickness depends on both the probe system (frequency, geometry) and the conductivity of the coating and the base metal. Its value should be determined experimentally, unless otherwise specified by the manufacturer.

NOTE A simple experiment to estimate the critical minimum base metal thickness is described in Annex D.

However, in the absence of any other information, the required minimum base metal thickness, t_{min}, can be estimated from Formula (2):

$$t_{min} = 3 \cdot \delta_0 \quad (2)$$

where δ_0 is the standard penetration depth of the base metal (see Annex A).

In cases of a non-conductive and non-magnetic base material, the base material thickness does not affect the measurement results and consequently it shall not be considered as an influencing factor.

5.4 Geometry — Edge effects

The induction of eddy currents is obstructed by geometric limitations of the coating (such as edges, drills and others). Therefore, measurements made too near to an edge or corner may not be valid unless the instrument has been specifically adjusted for such measurements. The necessary distance in order to avoid an impact of the edge effect depends on the probe system (field distribution).

NOTE 1 A simple experiment to estimate the edge effect is described in Annex D.

NOTE 2 Amplitude-sensitive eddy-current instruments as described in ISO 2360 can be substantially more affected by edge effects.

5.5 Geometry — Surface curvature

The propagation of the magnetic field and consequently the induction of eddy currents are affected by the surface curvature of the coating and the base material. This influence becomes more pronounced with decreasing radius of the curvature and decreasing coating thickness. In order to minimize this influence, an adjustment should be performed on a sample with the same geometry.

The influence of surface curvature depends considerably on the probe geometry and can be reduced by reducing the sensitive area of the probe. Probes with very small sensitive areas are often called "microprobes".

NOTE 1 There are instruments and probes available that are capable of automatically compensating the sample surface curvature influence if the curvature diameter is known. They can avoid the resulting thickness error.

NOTE 2 A simple experiment to estimate the effect of surface curvature is described in Annex D.

5.6 Surface roughness

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

In order to reduce the influence of roughness, a calibration should be carried out with reference parts with a roughness equivalent to the coated sample.

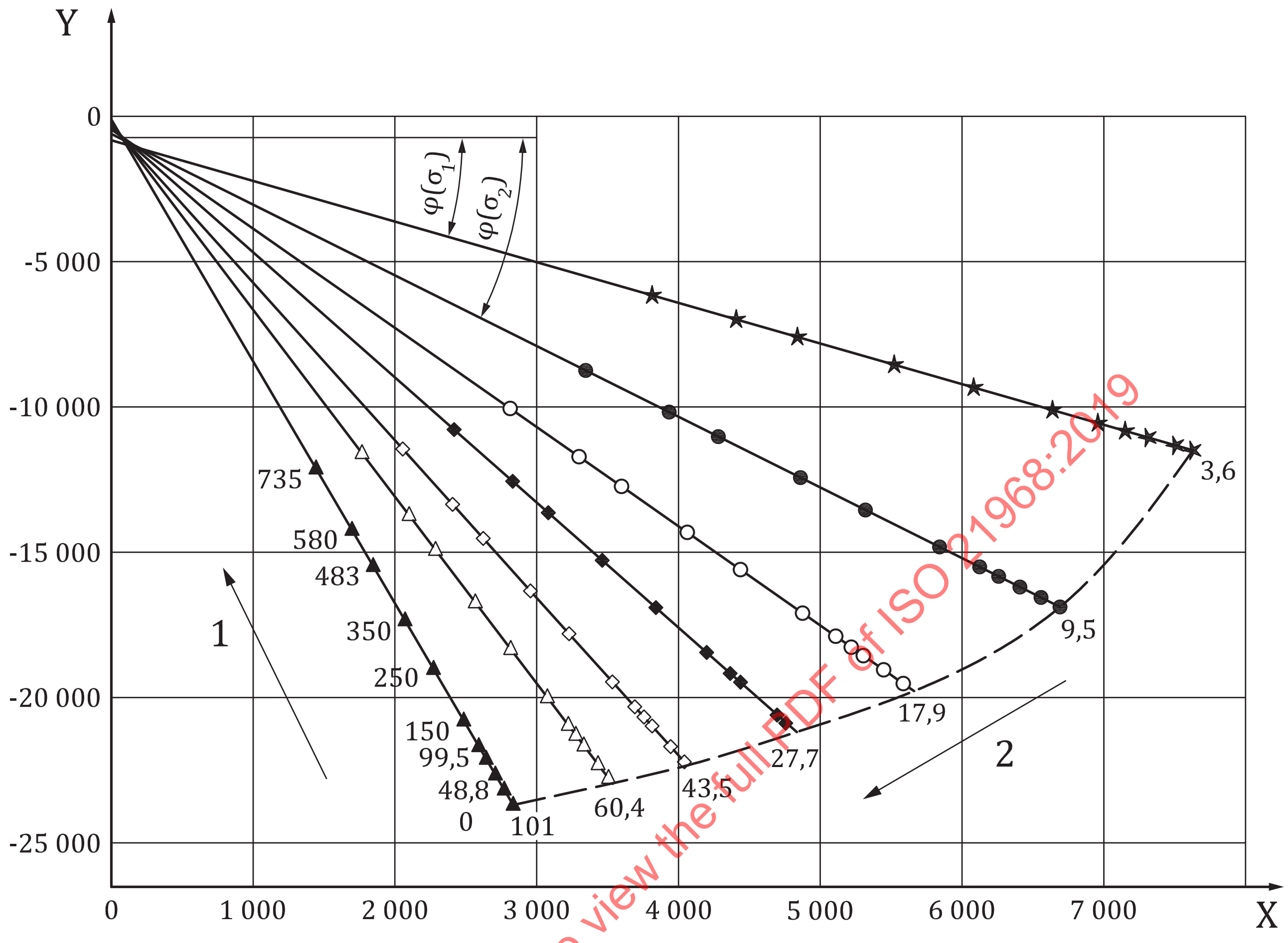
If necessary, the definition of the average coating thickness that is used should be stated between supplier and client.

NOTE Amplitude-sensitive eddy-current measurement as described in ISO 2360 can be more affected by base metal roughness.

5.7 Lift-off effect

If the probe is not placed directly onto the coating, the gap between probe and coating (lift-off) will affect the measurement of the metal coating thickness. The strength of the lift-off effect depends on the probe design and the resulting field geometry. By using appropriate electronic circuit design and/or a mathematical algorithm in the instrument, lift-off compensation can be applied for gaps of up to 1 mm.

The strength of the lift-off effect can be small for some probe designs. In this case, an increase of the lift-off height results mainly in a reduction of the impedance amplitude but only in a small change of the phase angle as a measure of the thickness (see Figure 3). The remaining influence can be compensated by an appropriate mathematical algorithm using the measured amplitude and phase angle information.



Key

—▲—	sample conductivity σ = 101,088 % IACS
—△—	sample conductivity σ = 60,407 % IACS
—◇—	sample conductivity σ = 43,48 % IACS
—◆—	sample conductivity σ = 27,688 % IACS
—○—	sample conductivity σ = 17,85 % IACS
—●—	sample conductivity σ = 9,534 % IACS
—★—	sample conductivity σ = 3,551 % IACS
1	increasing lift-off height in µm
2	increasing σ in % IACS
X	real part
Y	imaginary part

Figure 3 — Lift-off effect

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

NOTE 1 A simple experiment to estimate the lift-off effect is described in Annex D.

NOTE 2 Instead of lift-off compensation, the thickness of non-conductive coatings on top of conductive base metals can be measured by using the amplitude change as measuring effect (see Annex A).

5.8 Probe pressure

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

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

5.9 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 surface normal can cause measurement errors.

The possibility of tilt inadvertently occurring can be minimized by probe design or by using a probe holding jig.

5.10 Temperature effects

As temperature changes affect the characteristics of the probe, it should be used under approximately the same temperature conditions as when the instrument was calibrated.

The influence of temperature variations can be reduced by a temperature compensation of the probe. The manufacturer's specification shall be taken into account.

Most metals change their electrical conductivity with temperature. Because the measured coating thickness is influenced by changes in the electrical conductivity of the coating and the base material, large temperature changes should be avoided (see 5.2).

NOTE Temperature differences between the probe, the electronics of the instrument, the environment and the sample can cause large thickness errors. One example is the thickness measurement of hot coatings.

5.11 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 those of the coating or the base metal. If a difference does exist, then the measurements will, in addition, be affected by an intermediate coating thinner than t_{min}. If the intermediate coating is thicker than t_{min} and non-magnetic, it can be treated as the base metal (see 5.3).

5.12 External electromagnetic fields

The measurement results can be influenced by strong electromagnetic interfering fields. When observing unexpected results or a strong variation of results, which cannot be explained by other factors, this influence should be taken into account. In this situation, a comparison measurement should be carried out at a location without interfering fields.

6 Calibration and adjustment of the instrument

6.1 General

Before use, every instrument shall be calibrated or adjusted according to the instructions of the manufacturer by means of suitable thickness reference standards, base material and a reference standard with sufficient coating thickness as a saturation material. The material, geometry and surface properties of the base metal used for calibration or adjustment should be similar to those of the test specimens in order to avoid deviations caused by the factors described in Clause 5. Otherwise, these influences shall be considered in the estimation of the measurement uncertainty.

During calibration or adjustment, the instruments, the standards and the base material should have the same temperature as the test specimens to minimize temperature-induced differences.

In order to avoid the influence of instrument drift, periodic control measurements with reference standards or control samples are recommended. If required, the instrument shall be re-adjusted.

NOTE Most instruments automatically adjust themselves during a function called “calibration”, carried out by the operator, whereas the result of the calibration is often not obvious.

6.2 Thickness reference standards

Thickness reference standards for calibration and adjustment are either coated base materials or, if available, metal foils, which are placed onto uncoated base materials.

Metal foils and coatings shall have the same conductivity as the coatings to be measured. Thickness values of the reference standards and their associated uncertainties shall be known and unambiguously documented. The surface area for which these values are valid shall be marked. The thickness values should be traceable to certified reference standards.

The uncertainties shall be documented with their confidence level, for example U (95 %), i.e. the probability, that the “true” value is within the reported uncertainty interval around the documented thickness value, is minimum 95 %.

Prior to use, metal foils and coatings are to be checked visually for damage or mechanical wear as this would cause an incorrect adjustment and thus systematic deviation of all measurement values.

The use of metal foils as reference standards, compared to selected coated base metals, benefits from the possibility of placing the foils directly on each base material. The geometry influence and other factors are then already considered during the adjustment.

6.3 Methods of adjustment

Adjustment of the coating thickness gauges is executed by placing the probes on uncoated and/or one or more coated pieces of base metal with known coating thickness and a coated piece with a sufficiently high coating thickness, so that it can be used as a saturation standard. Depending on the instrument types, the instructions of the manufacturer and on the functional range of the instrument under use, adjustments can be carried out on the following items:

a) a piece of uncoated base material;

b) a piece of coated base material with a sufficiently high thickness (saturation standard);

c) a piece of uncoated base material and a piece of coated base material with a defined coating thickness;

d) a piece of uncoated base material and several pieces of coated base material with defined, but different, coating thicknesses;

e) a piece of uncoated base material, one or several pieces of coated base material with defined, but different, coating thicknesses and a piece of coated base material with a sufficiently high thickness (saturation standard);

f) several pieces of coated base material with defined, but different, coating thicknesses;

g) several pieces of coated base material with defined, but different, coating thicknesses and a piece of coated base material with a sufficiently high thickness (saturation standard).

According to 6.2, the term “coated base material” includes metal foils placed onto uncoated base material.

The stated adjustment methods may lead to different accuracies of the measuring results. Thus, a method should be used that best fits the given application and leads to the desired accuracy. The measuring uncertainty that can be achieved by the different adjustment methods depends on the evaluation algorithm of the gauges as well as on the material, geometry and surface condition of the standards and of the base metals to be measured. If the desired accuracy is not achieved by one method, a different adjustment method may lead to better results. In general, the measuring uncertainty can be reduced by increasing the number of adjustment points, which should be properly adapted to the thickness interval of the coating to be measured.

NOTE 1 The process used to adapt the probe to a given base material by placing the probe onto the uncoated base material, is often called “zeroing” or “zero point calibration”. However, even this procedure is an “adjustment” or part of an adjustment process as defined by this document. This type of adjustment is only necessary when the base material is a conductive material.

NOTE 2 Depending on how many pieces of coated and uncoated base metals are used to adjust the instrument, the corresponding adjustment method is often called “single-point”, “two-point” or “multiple-point adjustment”.

NOTE 3 The process used to adapt the probe to a given piece of coated base material with a sufficiently high thickness (saturation standard) is often called “saturation measurement” or “saturation calibration”. However, even this procedure is an “adjustment” or part of an adjustment process as defined by this document.

The measurement uncertainty resulting from an adjustment of the instrument cannot be generalized to all subsequent measurements. In each case, all specific and additional influencing factors shall be considered in detail, see Clause 5 and Annex D.

NOTE 4 Some types of gauges permit resetting the instrument to an original adjustment of the manufacturer. This adjustment is valid for the manufacturer’s uncoated or coated reference standards only. If these standards or the same types of standards are used to check the instrument after a period of use, any deterioration of gauge and probes, for example, wear of the probe by abrasion of the contact pole, can be recognized by observing deviations of the measuring results.

7 Measurement procedure and evaluation

7.1 General

Every instrument shall be operated according to the manufacturer’s instructions especially considering the factors affecting measurement accuracy discussed in Clause 5.

Before using the instrument and after changes affecting the measurement accuracy (see Clause 5), the adjustment of the instrument shall be checked.

To ensure that the instrument measures correctly, it shall be calibrated with valid standards at the place of inspection each time

a) the instrument is put into operation,

b) the material and geometry of the test specimens are changed, or

c) other conditions of the inspection have changed (for example temperature) where the effects are not known.

As not all changes of measurement conditions and their influences on the measurement accuracy can be immediately recognized (such as drift, wear of the probe), the instrument should be calibrated at regular time intervals while in use.

7.2 Number of measurements and evaluation

The coating thickness should be determined as the arithmetic mean of several single values, which are measured in a defined area of the coating surface. In addition to the mean, the standard deviation should be reported (see Annex B). The random part of the measurement uncertainty can be reduced by increasing the number of measurements. If not otherwise specified or agreed upon, it is recommended to measure at least five single values (depending on the application).

NOTE 1 From the standard deviation, a variation coefficient *V* can be calculated. *V* corresponds to the relative standard deviation (e.g. in percent) and enables a direct comparison of the standard deviation for different thicknesses.

NOTE 2 The total scatter of the measurement is composed of the scatter of the instrument itself and the scatter caused by the test specimen. The standard deviation of operator and probe in the measured thickness range is determined by repeated measurements at the same location, if necessary, with the help of an auxiliary device for placing the probe.

When measuring on rough coating surfaces or on test specimens with known large thickness gradients (for example due to their size and/or their shape), the reason for deviations between the single measurements should be determined by a series of measurements.

8 Uncertainty of the results

8.1 General remarks

A complete evaluation of the uncertainty of the measured thickness shall be carried out in accordance with ISO/IEC Guide 98-3. Details of the background of the expression of the uncertainty are summarized in Annex B. A typical example of this calculation is described in Annex F.

Uncertainty of the thickness measuring result is a combination of uncertainties from a number of different sources. Important sources that should be considered include the following:

a) uncertainty of the calibration of the instrument;

b) stochastic influences affecting the measurement;

c) uncertainties caused by factors summarized in Clause 5;

d) further influences, drifts, digitalization effects and other effects.

All uncertainty components shall be estimated and summarized to the combined standard uncertainty as described in ISO/IEC Guide 98-3, see Annex B.

A possible procedure for the estimation of the uncertainty is given in the following simplified approach (see 8.2 to 8.5).

The single uncertainty components of the listed sources are dependent on the respective measurements, the properties of the samples measured, the instrument, the environmental condition, etc. and can show large differences for different applications. Therefore, the single uncertainty components shall be estimated for each measurement in all detail. The quality of the uncertainty is determined by the quality of the estimation of all uncertainty components. Missing components result in wrong uncertainty estimations and consequently in wrong thickness results.

In particular, the factors listed in Clause 5 can result in large uncertainty values and should be minimized by an adjustment if possible.

NOTE In addition to the need to express the uncertainty in the result, the analysis of possible uncertainty components provides detailed information in order to improve the measurement.

8.2 Uncertainty of the calibration of the instrument

If no other information is given, the current uncertainty of an instrument can be estimated within a limited thickness range by realization of *n* repeated measurements on a given reference standard with known thickness t_r and uncertainty $U_r(k = 2)$. The measurement result is the arithmetic mean value $\overline{t_m}$ of the measured thickness values with the standard deviation $s(t_m)$. The quality of the calibration is determined by the ratio E of the resulting difference $\left|\overline{t_m} - t_r\right|$ and the combined uncertainty of the calibration measurement, see Formula (3). This uncertainty [see Formula (4), denominator of E, $k = 2$] is considered to be caused by the stochastic error of the measurement with n repeats (compare to 8.3) and the given reference standard uncertainty U_r. In case of $E \leq 1$, the calibration is valid and cannot be further improved by means of this reference standard, i.e. the difference cannot be distinguished from the uncertainty. Therefore, the standard uncertainty of the calibration $u_{cal}(k = 1)$ is given by the combined uncertainty of the verification measurement but with respect to the 1-sigma level ($k = 1$).

However, in the case of $E > 1$, a significant deviation of the calibration within the uncertainty is detected and an adjustment of the instrument should be carried out in order to improve the calibration accuracy.

$$E = \frac{\left|t_r - \overline{t_m}\right|}{2 \cdot u_{cal}} \tag{3}$$

$$u_{cal} = \sqrt{\left[t(68{,}27\,\%, n-1) \cdot \frac{s(t_m)}{\sqrt{n}}\right]^2 + \left[0{,}5 \cdot U_r\right]^2} \tag{4}$$

NOTE 1 In case the tolerance, T, of the reference standard is given instead of U_r, i.e. ($t_r \pm T$), for example in a certificate of a certified reference material, the respective standard uncertainty (for 68,3 % confidence level) can be calculated as $u_r = T / \sqrt{3}$ and the expanded uncertainty (for 95,4 % confidence level) as $U_r = 1{,}653 \cdot T / \sqrt{3}$. The deviation from the usual factor of two for normal distribution is due to the fact that tolerances follow rectangular distributions.

The calibration uncertainty u_{cal} is only valid in a small thickness range around t_r. In the case of a larger thickness range of interest, the uncertainty u_{cal} should be estimated on both sides of the thickness range. The linear interpolation between both values gives the uncertainty of interest as a function of the thickness.

Very often, the accuracy of the calibration is limited by the given uncertainty of the reference standard, as the uncertainty of the calibration cannot be smaller than the uncertainty of the reference standard used. In order to improve the calibration, a reference standard with a smaller uncertainty is necessary.

Usually, a normalization or zeroing on an uncoated base metal is recommended by the manufacturer at the beginning of a measurement. The resulting uncertainty of this normalization is considered to be already included in u_{cal}.

NOTE 2 $t(68{,}27\ \%, n - 1)$ is the student factor (degrees of freedom $f = n - 1$ and level of confidence with $P = 68{,}27$ %). Respective values are summarized in Annex E.

8.3 Stochastic errors

In general, repeated measurements are recommended in order to improve the accuracy of the arithmetic mean value $\overline{t}$ of the thickness values measured (see 7.2), i.e. to reduce the uncertainty of the thickness result. In the case of n repeated measurements, the standard uncertainty $u_{sto}(k = 1)$ of the arithmetic mean $\overline{t}$ can be estimated by (Type A), as shown by Formula (5):

$$u_{sto} = t(68{,}27\%, n-1) \cdot \frac{s(t)}{\sqrt{n}} \tag{5}$$

The standard uncertainty u_{sto} is a measure of all errors arising from unpredictable or stochastic temporal and spatial variations of influence quantities.

NOTE 1 The standard uncertainty u_{sto} can be reduced by increasing the number of repeated measurements. This can be important, for example, in cases of rough sample surfaces.

NOTE 2 Not all contributions to the uncertainty u_{sto} are of random nature (Type A). This depends on the design of experiment. For example, the measured thickness of a larger sample with a thickness gradient results in a high uncertainty u_{sto} because of the systematic thickness variation. In the case of a reduced measurement area, u_{sto} is reduced and the arithmetic mean value $\bar{t}$ gives a better description of the local thickness.

Care should be taken to address the risk that Type B standard uncertainties (see e.g. 8.4), which might contribute to Type A standard uncertainties, are not counted twice.

8.4 Uncertainties caused by factors summarized in Clause 5

The influence of the factors summarized in Clause 5 should be minimized by means of an adjustment whenever this is possible. Very often, these influences can only be estimated. The resulting uncertainty shall be considered as a component of the combined uncertainty of the measurement. Simple experiments to estimate the uncertainty of some of these factors are described in Annex D. Usually, the influence of these factors, and therefore the resulting uncertainties, are a function of thickness. Consequently, in order to estimate the uncertainty for a given thickness or for, at least, a small thickness range, the experiments shall be carried out with samples with the thickness of interest.

For example, the variation of the conductivity of the base metal is considered. As described in Annex B, the expected variation should be estimated for the thickness of interest. The resulting thickness variation with respect to the selected reference base material should be $\Delta t_{bm} = |t_{min} - t_r|$ or $\Delta t_{bm} = |t_{max} - t_r|$. This gives the standard uncertainty caused by the variation of the base metal properties $u_{bm}(k = 1)$, as shown by Formula (6):

$$u_{bm} = \frac{\Delta t_{bm}}{\sqrt{3}} \tag{6}$$

The same estimation of the standard uncertainty shall be carried out for all relevant factors listed in Clause 5. For example, in the case of an expected variation of the surface curvature resulting in Δt_{cs} with respect to the procedure D.4, the standard uncertainty can be estimated as $u_{cs}(k = 1)$, as shown by Formula (7):

$$u_{cs} = \frac{\Delta t_{cs}}{\sqrt{3}} \tag{7}$$

In case the influence of a factor is minimized by means of an adjustment, the remaining uncertainty shall be considered.

Some of these factors influencing the accuracy, such as base metal properties (5.3) or surface curvature (5.5), can be minimized if the calibration is carried out with flexible foils as reference standards on a base metal with identical material and curvature properties as the sample of interest. In this case, only the expected variations of the sample properties shall be considered.

8.5 Combined uncertainty, expanded uncertainty and final result

The combined uncertainty summarizes all standard uncertainty components (8.2, 8.3, 8.4 and any potential others). In the simplified approach described, when estimating the uncertainties for a given thickness or a very small thickness range, the sensitivity coefficients can be considered to be equal to one (see Annex B). This results in the combined uncertainty u_c, as shown by Formula (8):

$$u_c = \sqrt{u_{cal}^2 + u_{sto}^2 + u_{bm}^2 + u_{cs}^2 + \ldots} \tag{8}$$

As the final result, the expanded uncertainty $U(k = 2)$ is calculated (2-sigma level, 95,45 %), as shown by Formula (9):

$$U(k=2) = 2u_c \tag{9}$$

And the complete result of the measurement with the thickness value $\bar{t}$, as shown by Formula (10):

$$t = \bar{t} \pm U(k=2) \tag{10}$$

9 Precision

9.1 General

See Annex G for further information on determining precision.

9.2 Repeatability (r)

Repeatability, r, is the value less than or equal to which the absolute difference between two test results obtained under repeatability conditions may be expected to be, with a probability of 95 % (according to ISO 5725-1:1994, 3.16). The repeatability limit, r, in accordance with this document and calculated with a probability of 95 %, is given in Table 1 for typical applications of this measurement technique.

Table 1 — Repeatability limit (r)

Application	Thickness t µm	Repeatability limit r µm
Cu/Epoxy	4,9	0,033
	16,7	0,042
	32,1	0,078
	64,0	0,092
Foil/Cu/Epoxy	4,9	0,028
	16,6	0,038
	31,8	0,062
	63,7	0,082
NOTE "Foil" represents a possible non-conductive coating on top of the metal coating of interest, such as a protective lacquer. The foil thickness used is approximately 75 µm.		

Table 1 *(continued)*

Application	Thickness t µm	Repeatability limit r µm
Cu/Fe	3,5	0,23
	5,2	0,21
	9,3	0,28
	11,0	0,32
	14,1	0,19
	19,3	0,18
	26,1	0,64
Foil/Cu/Fe	3,5	0,21
	11,0	0,28
	14,1	0,22
	19,4	0,14
	26,2	0,59
Zn/Fe	6,2	0,07
	7,7	0,29
	12,1	0,25
	16,5	0,31
	23,3	0,45
	28,1	1,31
	35,5	1,8
Foil/Zn/Fe	6,2	0,06
	12,0	0,12
	16,4	0,31
	23,2	0,34
	35,5	1,56
Ni/Fe	5,1	0,21
	6,1	0,16
	9,6	0,16
	13,2	0,36
	16,8	0,72
	21,7	0,7
	27,6	1,19
Foil/Ni/Fe	6,5	0,15
	10,0	0,16
	13,4	0,37
	22,0	0,66
	27,6	1,19

NOTE “Foil” represents a possible non-conductive coating on top of the metal coating of interest, such as a protective lacquer. The foil thickness used is approximately 75 µm.

9.3 Reproducibility limit (R)

Reproducibility limit, R, is the value less than or equal to which the absolute difference between two test results obtained under reproducibility conditions may be expected to be, with a probability of 95 % (according to ISO 5725-1:1994, 3.20). The reproducibility limit, R, in accordance with this document and calculated with a probability of 95 %, is given in Table 2 for typical applications of this measurement technique.

Table 2 — Reproducibility limit (R)

Application	**Thickness** t µm	**Reproducibility limit** R µm
Cu/Epoxy	4,9	0,052
	16,7	0,181
	32,1	0,105
	64,0	0,827
Foil/Cu/Epoxy	4,9	0,126
	16,6	0,169
	31,8	0,150
	63,7	0,887
Cu/Fe	3,5	0,30
	5,2	0,45
	9,3	0,28
	11,0	0,62
	14,1	0,27
	19,3	0,40
	26,1	0,72
Foil/Cu/Fe	3,5	0,22
	11,0	0,51
	14,1	0,32
	19,4	0,40
	26,2	0,77
Zn/Fe	6,2	0,11
	7,7	0,90
	12,1	0,31
	16,5	0,39
	23,3	0,89
	28,1	1,81
	35,5	2,24
Foil/Zn/Fe	6,2	0,13
	12,0	0,18
	16,4	0,57
	23,2	0,72
	35,5	2,15
NOTE "Foil" represents a possible non-conductive coating on top of the metal coating of interest, such as a protective lacquer. The foil thickness used is approximately 75 µm.		

Table 2 *(continued)*

Application	Thickness *t* µm	Reproducibility limit *R* µm
	5,1	0,36
	6,1	0,40
	9,6	0,46
Ni/Fe	13,2	1,24
	16,8	1,58
	21,7	1,66
	27,6	2,82
	6,5	0,38
	10,0	0,52
Foil/Ni/Fe	13,4	0,88
	22,0	1,53
	27,6	2,40
NOTE “Foil” represents a possible non-conductive coating on top of the metal coating of interest, such as a protective lacquer. The foil thickness used is approximately 75 µm.		

10 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 document, including its year of publication, i.e. ISO 21968:2019;

c) the sizes of the test areas over which the measurements were made in square millimetres (mm^2), other units 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 test, 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 test was carried out, including the results of the individual determinations and their arithmetic mean;

h) the name of the operator and testing organization;

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

j) any deviation from the method specified;

k) the date of the test.

Annex A
(informative)

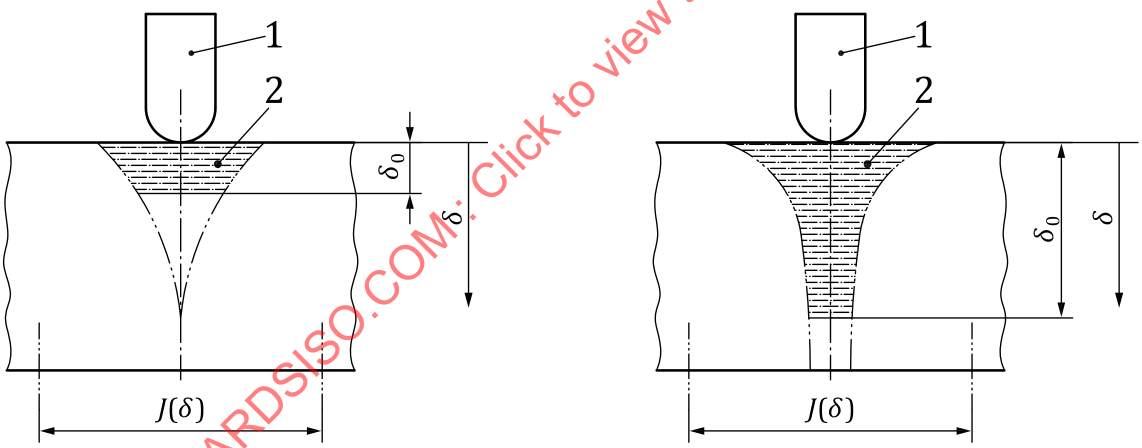
Eddy-current generation in a metallic conductor

A.1 General

Eddy-current instruments work on the principle that a high-frequency electromagnetic field generated by the probe system of the instrument produces eddy currents in an electrical conductor on which the probe is placed. These induced eddy currents cause a change of the electromagnetic field surrounding the probe coil system and therefore result in a change of the amplitude and/or the phase of the probe coil impedance, which can be used as a measure of the thickness of the conductor.

The eddy-current generation in a metal conductor is shown in Figure 1.

The eddy-current density $J(\delta)$ changes its magnitude with increasing thickness of the conductor (depth). At the depth δ_0 (standard penetration depth), the electromagnetic field and consequently the current density drops to $\frac{J(\delta_0)}{J(0)} = \frac{1}{e}$. In principle, this standard penetration depth is determined by the sample conductivity, the permeability and the frequency of the probe coil system, see Figure A.1.



a) High frequency or/and high conductivity   b) Low frequency or/and low conductivity

Key

1 probe
2 eddy currents
δ_0 standard depth of penetration
δ depth
$J(\delta)$ (magnitude of) eddy-current density

Figure A.1 — Schematic to show the influence of frequency and conductivity on the standard penetration depth

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

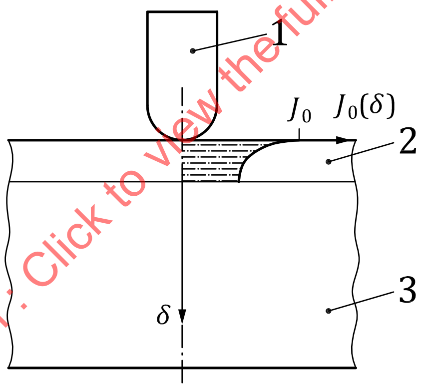
$$\delta_0 = \frac{503}{\sqrt{f \cdot \sigma \cdot \mu_r}} \cdot F_p \qquad (A.1)$$

where

- f is the probe operating frequency, in Hertz;
- σ is the electrical conductivity of the conductor, in Megasiemens per metre;
- μ_r is the relative permeability of the conductor (for non-magnetic materials $\mu_r = 1$);
- F_p is a correction factor determined by the geometry of the probe.

A.2 Example 1 — Conductive coating on a non-conductive base material

In this case, the eddy-current density is determined only by the thickness of the conductive coating (see Figure A.2). A changed coating thickness results in a changed interaction of the magnetic field of the probe with the conductive coating and consequently the eddy-current density is affected. This effect causes a change of the phase angle of the test coil impedance and consequently it can be used as a measure of the coating thickness (see Figure 2, thickness local curve).



Key

1 probe

2 conductive coating

3 non-conductive base material

Figure A.2 — Schematic of the eddy-current density in the case of a conductive coating on a non-conductive material

The approximate maximum measurable thickness, t_{max}, in mm, may be calculated from Formula (A.2):

$$t_{max} = 0{,}8\,\delta_0 \qquad (A.2)$$

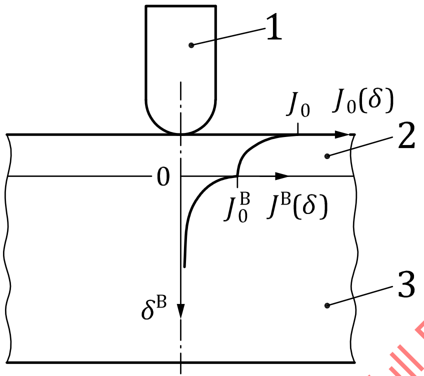
The thickness range is limited by the penetration depth δ_0. If the conductive coating thickness is increased further, the resulting increase of the generated eddy-current density starts to become smaller, i.e. the measurement sensitivity will be reduced.

The amplitude-sensitive eddy-current method (see ISO 2360) is also capable of measuring a conductive coating on top of a non-conductive material. However, the phase-sensitive eddy-current method gives in most applications better results (accuracy and repeatability) and is therefore the suitable method for this situation.

A.3 Example 2 — Conductive coating on a conductive and/or magnetic base metal

In this case, the generated eddy-current density is determined by the thickness and conductivity of the coating and the conductivity and permeability of the base metal (see Figure A.3). The coating thickness can only be measured by means of the phase-sensitive eddy-current method.

A changed coating thickness results in a changed interaction of the magnetic field of the probe with the conductive coating and consequently the eddy-current density of the coating and the base metal is affected. This effect causes a change of the phase angle of the test coil impedance and consequently it can be used as a measure of the coating thickness (see Figure A.4, thickness local curve of Zn/steel). The material properties of the base metal (conductivity or/and permeability) should be constant for all measurements, otherwise the thickness can be affected, resulting in thickness errors.



Key

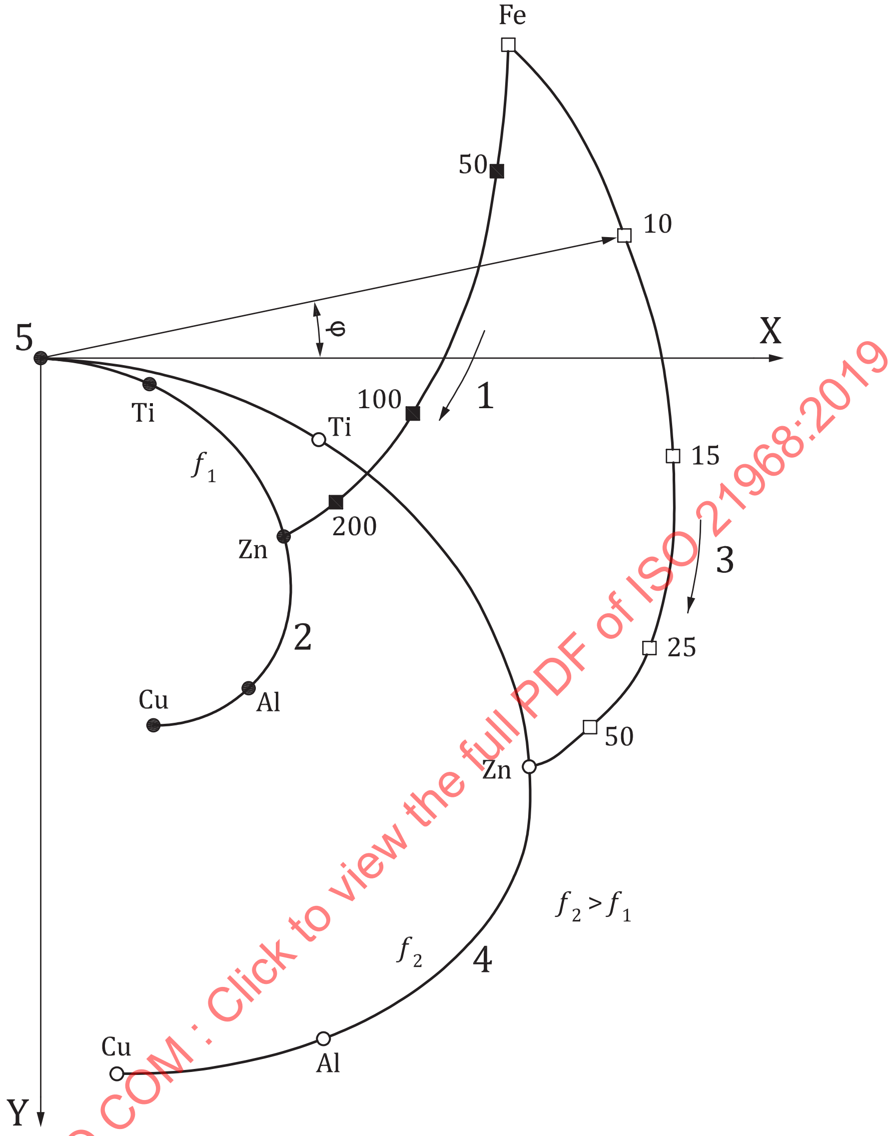
1 probe

2 conductive coating

3 conductive base metal

Figure A.3 — Schematic of the eddy-current density in the case of a conductive coating on a conductive and/or magnetic base metal

Dimensions in micrometres



Key

1 thickness local curve of Zn on top of steel (Fe) for frequency f_1

2 conductivity local curve for frequency f_1

3 thickness local curve of Zn on top of steel (Fe) for frequency f_2

4 conductivity local curve for frequency f_2

5 coil in air (unaffected)

X real part

Y imaginary part

Figure A.4 — Thickness local curve of Zn on top of steel (Fe) in the normalized impedance plane for two frequencies f_1 and f_2

The permeability of the base metal and the generated eddy currents affect the measurement in an opposite way. In the case of an uncoated magnetic base metal (such as steel), both properties result in the impedance vector shown in Figure A.4 at the point "Fe". With increasing coating thickness, the eddy-current influence becomes more and more pronounced resulting in the shown local curve.

The conductivity of both coating and base metal should show a difference at least of a factor of two. With increasing conductivity difference, the measuring effect becomes more and more pronounced, i.e. the thickness accuracy increases. Contrary, the accuracy is limited by a conductivity factor below two.

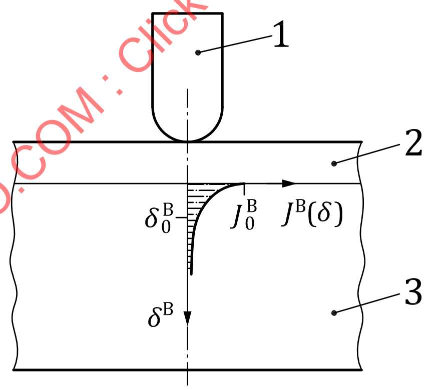
It is also possible to measure the thickness of magnetic coatings on top of magnetic base metals, such as Ni/steel. However, all material properties of the coating and the base metal, especially their conductivities and permeabilities, should be constant to avoid thickness errors.

The amplitude-sensitive eddy-current method (see ISO 2360) is only capable of measuring a conductive coating on top of a non-conductive material. In the case of a conductive coating on top of a conductive base metal, the amplitude-sensitive method cannot distinguish between the coating and the base metal, i.e. the entire eddy-current density generated in the coating and the base metal would be used to determine the coating thickness. This results in incorrect thickness values.

A.4 Example 3 — Non-conductive coating on a conductive and/or magnetic base metal

In this case, the eddy-current density is only determined by the distance between the probe and the base metal, i.e. the non-conductive coating thickness (see Figure A.5). The resulting change of the impedance amplitude (lift-off effect) can also be used to measure this thickness, i.e. the phase-sensitive eddy-current method can also be used instead of the amplitude-sensitive eddy current method (see ISO 2360) or the magnetic inductive method (see ISO 2178).

Furthermore, the phase-sensitive eddy-current method can also be used to measure non-conductive coatings on top of conductive coatings on top of a conductive and/or magnetic base metal, such as paint/Zn/steel. However, the impedance amplitude (lift-off effect) as a function of the non-conductive coating thickness is affected by the thickness of the conductive coating beneath (see Figure A.6). This should be considered in the calibration of the probe or respective algorithms should be used that are able to calculate the correct thickness as a function of the conductive layer's properties (thickness, conductivity, permeability).



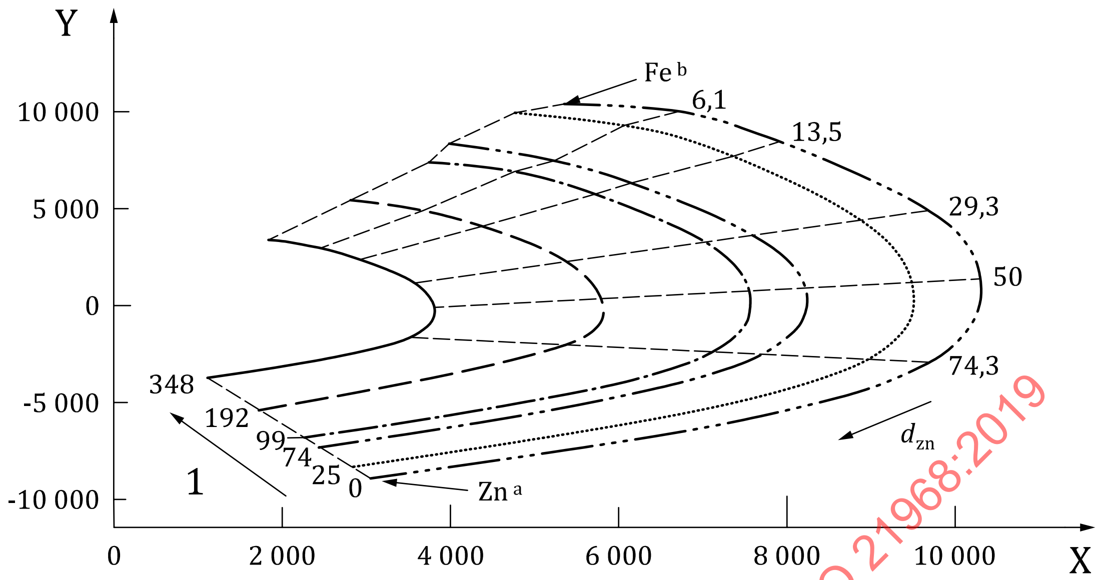
Key

1 probe

2 non-conductive coating

3 conductive base metal

Figure A.5 — Schematic of the eddy-current density in the case of a non-conductive coating on a conductive and/or magnetic base metal



Key

X real part

Y imaginary part

1 lift-off height in µm

a Saturation thickness of coating.

b Uncoated base material.

NOTE The paint coating thickness corresponds to the lift-off height and can be measured.

Figure A.6 — Thickness local curve of Zn on top of steel (Fe) beneath a paint coating in the normalized impedance plane for *f* = 240 kHz

Annex B
(informative)

Basics of the determination of the uncertainty of a measurement of the used measurement method corresponding to ISO/IEC Guide 98-3

B.1 General

Coating thicknesses are generally determined as the mean value of several single measurements that are carried out at a fixed section of the layer's surface.

Based on these measurements, a mean value is allocated to the measurand "coating thickness". An uncertainty value is assigned, which provides information about the reliability of the allocated value.

Analysis is carried out progressively and begins by drawing up a model equation that shows the functional correlation between the indicated output value t and all the relevant influence quantities H_i, as shown by Formula (B.1):

$$t = F\left(H_0, H_1, H_2, \ldots H_i \ldots H_n\right) \tag{B.1}$$

Every influence quantity has a sensitivity coefficient c_i, which indicates how strong a modification ΔH_i affects the result t.

When the function F is given as analytic expression, the sensitivity coefficients may be calculated by partial derivation, see Formula (B.2):

$$c_i = \frac{\delta t}{\delta H_i} \tag{B.2}$$

If the kind of the functional correlation is unknown, an approximation by means of polynomial functions is recommended.

In many practical cases, this formulation is expressed by a linear dependence, i.e. the sensitivity coefficients become constant. This situation arises, for example, in sections of limited coating thickness.

In order to summarize the uncertainties of various error influences appropriately, all single uncertainty components may be referred to a level of confidence of 68,27 %, the so-called "standard uncertainty".

There are two types of uncertainties: Type A (see B.2) and Type B (see B.3).

B.2 Type A

The standard uncertainty of Type A is a measure of all random errors arising from unpredictable or stochastic temporal and spatial variations of influence quantities.

The standard uncertainty corresponds to the point of confidence of the mean value, see Formulae (B.3) and (B.4):

$$u_{\mathrm{sto}} = t(68{,}27\,\%, n-1) \cdot \frac{s(t)}{\sqrt{n}} \tag{B.3}$$

where s is the empirical standard deviation of the n repetition measurements,

$$s = \sqrt{\frac{\sum_{j=1}^{n} \left(\bar{x} - x_j\right)^2}{n-1}} \tag{B.4}$$

and $t(68{,}27\,\%, n - 1)$ the student factor (degrees of freedom $f = n - 1$ and level of confidence with $P = 68{,}27\,\%$).

Respective values are summarized in Annex E.

B.3 Type B

Many influencing factors or errors are not to be described by Type A, such as the influencing factors of Clause 5. These are classified as Type B.

In order to realize a balanced combination of those error influences with the uncertainties of Type A, ad hoc probability factors are allocated. In many practical cases, the influencing factors treated here are described by a uniform distribution (rectangle distribution).

If an influence quantity deviates by ΔH_i, the resulting uncertainty can be calculated as shown by Formula (B.5):

$$u_{\mathrm{B}} = \frac{\left| t_{\max} - t_{\min} \right|}{\sqrt{12}} \tag{B.5}$$

These fluctuations are generally estimated or determined experimentally (see Annex D).

In many applications, known uncertainties can be used for the uncertainty determination. A typical example is a given uncertainty of a thickness reference standard. To release this, take into consideration that these statements of uncertainty are converted into the standard uncertainty, for example, $U(k = 2)$ follows the standard uncertainty shown by Formula (B.6):

$$u(68{,}27\,\%) = \frac{U(95{,}45\,\%)}{2} \tag{B.6}$$

In order to summarize all investigated uncertainties, the so-called “combined uncertainty” is calculated. This is done by multiplying all standard uncertainties by their sensitivity coefficients and adding them up squared. In a simplified case, the sensitivity coefficients c_i equal one, see Formula (B.7):

$$u = \sqrt{\sum_i \left(c_i u_i\right)^2} \tag{B.7}$$

Multiplying with an indicated coverage factor of $k \geq 2$ results in an expanded uncertainty, which should be indicated in the actual result, see Formula (B.8):

$$U = k \cdot u \tag{B.8}$$

Annex C
(informative)

Basic performance requirements for coating thickness gauges based on the phase-sensitive eddy-current method described in this document

C.1 Technical specification

The manufacturer's technical specification should at least provide the following technical information for instruments and probes:

a) the principle of measurement;

b) the measuring range;

c) basic information on measuring uncertainty or the permissible error of measurement if measuring is carried out under conditions specified by the manufacturer;

d) information on how measuring results are influenced by the material, the curvature, thickness of the of the base metal, the edge effect (measurements close to an edge) and the lift-off-effect;

e) the battery operating time;

f) the function of an undervoltage monitor and automatic undervoltage switch-off;

g) the permissible operating temperature;

h) the permissible storage temperature;

i) available methods for calibration and adjustment;

j) the contact force of probes with spring loaded guiding sleeves;

k) the availability of temperature compensation;

l) the measuring rate;

m) the data memory (design, capacity, data communication);

n) the size and weight of the instrument (with batteries) and probes.

C.2 Check/verification of instruments and probes

C.2.1 Prior to the supply, after repair and at regular intervals after use

After the instruments and probes have been adjusted according to the manufacturer's instructions, the measuring accuracy should be checked and verified using a plane and uncoated base metal and a representative number of coated calibration standards or calibration foils, for which the coating or foil thicknesses should be equally distributed within the measuring range of the respective probe.

The aim of the check/verification of the instruments is to ensure that the thickness deviations are within the manufacturer's technical specification.

C.2.2 Performed on site

The accuracy of the instruments and probes should be verified daily. After the instrument has been adjusted according to the manufacturer's instructions, make a verification with an appropriate number of coated calibration standards made from the same base metal as the items to be measured or by means of calibration foils put onto the base metal to be measured. Their thicknesses should cover the expected coating thickness range. If curved coated items need to be measured, verification should be executed on items of the same base metal, geometry and curvature as the items to be measured.

The aim of the check/verification of the instruments is to ensure that the thickness deviations are within the manufacturer's technical specification.

Annex D
(informative)

Examples for the experimental estimation of factors affecting the measurement accuracy

D.1 General

Factors affecting the measurement accuracy are summarized and described in Clause 5. In practical measurements, it is important to estimate the influence of these factors or the resulting uncertainty. Therefore, some examples of simple experiments are described in this annex in order to show how the influence of these factors can be estimated. These experiments also provide a basis for estimating the respective uncertainty.

The factors described in D.2 to D.5 can cause differently pronounced influences for an instrument working with combined measuring principles in one probe. Consequently, the factors should be estimated separately for each measuring principle.

D.2 Edge effect

A simple edge effect test to assess the effect of the proximity of an edge uses a clean, uncoated and even sample of the base metal and follows the procedure described in steps 1 to 4 below. The procedure is illustrated in Figure D.1.

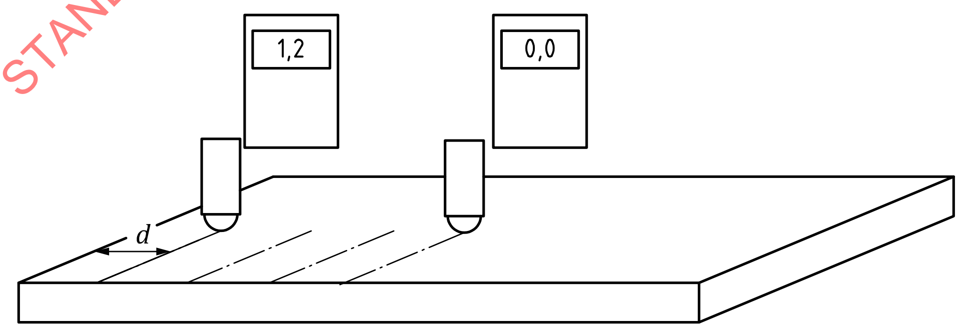
a) Step 1: Place the probe on the sample, sufficiently away from the edge.

b) Step 2: Adjust the instrument to read zero.

c) 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 tolerance.

d) Step 4: Measure the distance *d* from the probe to the edge (see Figure D.1).

The instrument may be used without correction provided that the probe is farer from the edge than the distance *d* as measured above. If the probe is used closer to the edge, a special adjustment is required or the additional resulting uncertainty for the used distance needs to be considered. If necessary, refer to the manufacturer's instructions.



Key

d distance from the probe to the edge

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

D.3 Base metal thickness

This influencing factor is only relevant in cases where the base material is conductive, i.e. a base metal. For a non-conductive base material, its thickness influence can be neglected.

A simple test to prove that the base metal thickness t_0 is larger than the critical minimum base metal thickness, t_0^{crit}, uses two (or more) clean, uncoated and even samples of the base metal with the thickness of interest and follows the procedure described in steps 1 to 4 below. The procedure is illustrated in Figure D.2.

a) Step 1: Place the probe on the first sample. It should be proven that the reading is not affected by the edges of the sample (see D.2).

b) Step 2: Adjust the instrument to read zero.

c) Step 3: Place the second sample beneath the first one, place the probe on top of this stack and check the instrument reading. If the instrument reading is still zero with respect to the expected uncertainty, the base metal thickness t_0 is larger than the critical minimum base metal thickness t_0^{crit} and no additional uncertainty is to be considered. If the instrument reading changes negatively with respect to the expected uncertainty, t_0 is smaller than t_0^{crit}, i.e. the measurement is affected by the too-small base metal thickness.

d) Step 4: If t_0 is smaller than t_0^{crit}, place a third sample beneath the stack of step 3, place the probe on top of this stack and check the instrument reading. If the instrument reading is still the same as in step 3 with respect to the uncertainty, the critical minimum base metal thickness lies within $t_0 < t_0^{crit} < 2t_0$. If the instrument reading shows a larger negative value than in step 3 then $2t_0$ is still smaller than t_0^{crit}. Continue to stack further samples in order to estimate t_0^{crit}.

The instrument may be used without correction provided that the base metal thickness t_0 is larger than t_0^{crit}. If t_0 is smaller than t_0^{crit}, a special adjustment is required and it should be considered that possible base metal variations cause an increase of the respective thickness uncertainty.

The experimentally determined critical minimum base metal thickness t_0^{crit} can be used to estimate the resulting uncertainty.

In order to improve the accuracy of the estimation of t_0^{crit}, samples with smaller thickness than t_0 should be used.

If the instrument does not display negative values, it is recommended to use a thin foil (e.g. 10 µm) between the probe and base metal to observe the decrease of the thickness.

NOTE The procedure to stack several samples in order to simulate an increase of the base metal thickness allows a good estimation of t_0^{crit} because the impact of the air gap between the samples on the eddy-current generation in the sample stack in comparison to the respective homogeneous material is almost negligible (eddy-current flow is perpendicular to the probe axis). Therefore, this simplified procedure can be carried out more easily with good results instead of producing base metals with variable thickness.

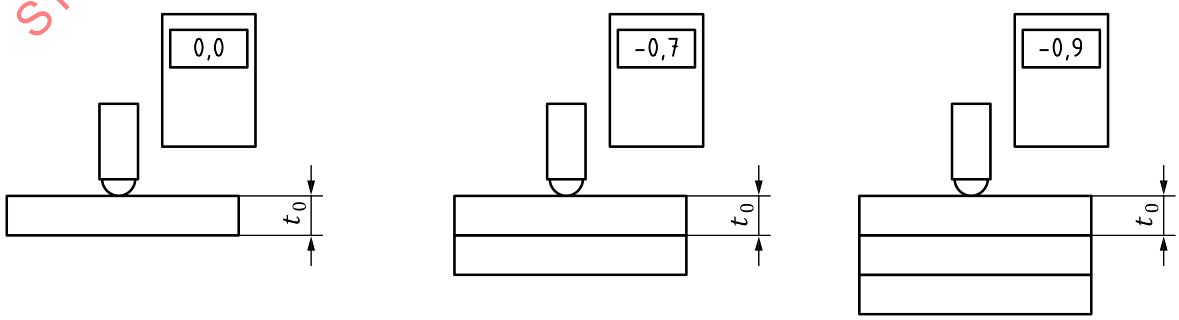


Figure D.2 — Schematic representation of the test for base metal thickness

D.4 Surface curvature

A simple test to assess the effect of the influence of the sample surface curvature uses a clean uncoated sample of the base metal with different curvature diameters (e.g. cylinder) and follows the procedure described in steps 1 to 3 below. All samples for this test should have the same material properties as the base metal of the sample of interest. The procedure is illustrated in Figure D.3 using the example of a convex curvature.

a) Step 1: Place the probe on an even sample (no curvature). It should be proven that the reading is not affected by the edges of the sample (see D.2) and that the base metal thickness of the sample is larger than the critical minimum base metal thickness (see D.3).

b) Step 2: Adjust the instrument to read zero.

c) Step 3: Place the probe on each sample starting with the largest available diameter and then continue the test with decreasing sample diameters. Note the diameter where a change of the instrument reading (positive increase) occurs with respect to the expected uncertainty or to the given thickness tolerance.

The instrument may be used without correction provided that the sample of interest shows a larger diameter than the noted one. If the diameter is smaller, an adjustment or special calibration correction is required or the additional resulting uncertainty for the used curvature should be considered. If necessary, refer to the manufacturer's instructions.

In practical situations, the diameter of the samples of interest varies very often. In this situation, the smallest and the largest diameter expected should be estimated and the instrument should be adjusted on an uncoated sample close to the average diameter. As a result, the measured deviation for the smallest and largest diameter can be estimated from the described procedure and used to estimate the uncertainty. Take this uncertainty into account during the measurement.

In order to improve the accuracy of the estimation of the curvature influence, increase the number of samples with different diameters.

NOTE The same procedure can be used in cases where the samples show a concave curvature, however, this concave curvature results in negative thickness readings. If the instrument does not display negative values, it is recommended to use a thin foil (such as10 µm) between the probe and base metal to observe the decrease of the thickness.

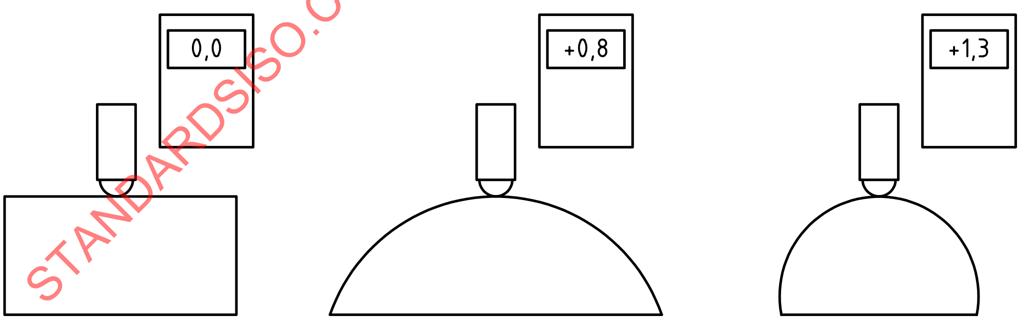


Figure D.3 — Schematic representation of the test for curvature effect

D.5 Conductivity and permeability of the base metal

This influencing factor is only relevant in cases where the base material is conductive, i.e. a base metal. For a non-conductive base material, this influencing factor can be neglected.

In practical situations, the conductivity of the base metal varies very often. A simplified procedure described in steps 1 to 5 below helps to reduce this influence and to estimate the resulting uncertainty.

This procedure requires several uncoated, clean and even samples representing approximately the expected variation of the base metal. The procedure is illustrated in Figure D.4.

a) Step 1: Place the probe on one of the samples. It should be proven that the reading is not affected by the edges of the sample (see D.2), that the base metal thickness of the sample is larger than the critical minimum base metal thickness (see D.3) and that the sample is even (no curvature, see D.4).

b) Step 2: Adjust the instrument to read zero.

c) Step 3: Place the probe on each of the samples and notice the reading. It is recommended to carry out repeated measurements on each sample and to use the average value in the next steps.

d) Step 4: Calculate the average of the readings of all samples and select the sample with the smallest deviation from this average.

e) Step 5: Use this selected sample as a reference base metal to carry out the zero adjustment for all measurements.

The instrument may be used without correction provided that the deviation of the sample with the smallest reading (or with the largest reading) from the calculated average value is smaller than the expected uncertainty or the given thickness tolerance.

If there are larger variations, the selected sample should be used as a reference base metal and the estimated deviation of the readings of the described procedure can be used to estimate the uncertainty. Take this uncertainty into account during the measurements.

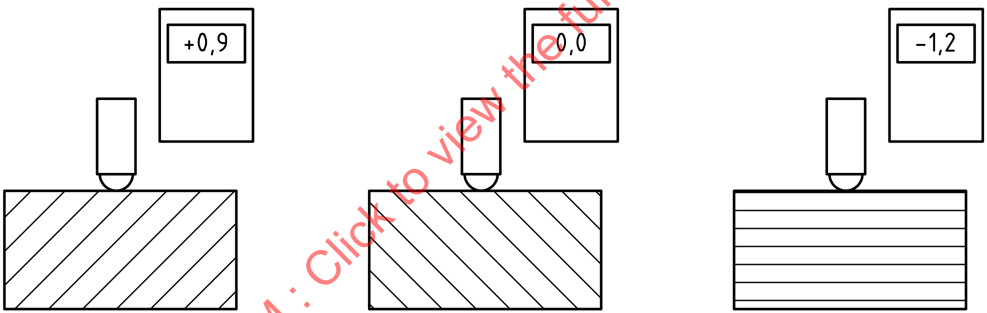


Figure D.4 — Schematic representation of the test for base metal conductivity test

D.6 Lift-off-height

In practical situations, very often the thickness of a conductive coating beneath a non-conductive paint (protective lacquer) needs to be measured or, in cases of a contactless measurement, the probe is placed above the sample surface. A simplified procedure described in steps 1 to 5 below helps to estimate the resulting uncertainty by this lift-off effect in case the lift-off effect is not compensated. This procedure requires several non-conductive, clean and even foils with different thicknesses representing approximately the expected variation of the non-conductive paint thickness or the measuring height. The procedure is illustrated in Figure D.5.

a) Step 1: Place the probe on one of the samples. It should be proven that the reading is not affected by the edges of the sample (see D.2), that the base metal thickness of the sample is larger than the critical minimum base metal thickness (see D.3) and that the sample is even (no curvature, see D.4).

b) Step 2: Read the coating thickness of the conductive coating.

c) Step 3: Place a non-conductive foil on top of the sample, place the probe on the foil and notice the reading. It is recommended to carry out repeated measurements and to use the average value in the next steps.