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**Non-conductive coatings on non-  
magnetic electrically conductive base  
metals — Measurement of coating  
thickness — Amplitude-sensitive  
eddy-current method**

*Revêtements non conducteurs sur matériaux de base non  
magnétiques conducteurs de l'électricité — Mesurage de l'épaisseur  
de revêtement — Méthode par courants de Foucault sensible aux  
variations d'amplitude*

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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.

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](http://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](http://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 on 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 the following URL: [www.iso.org/iso/foreword.html](http://www.iso.org/iso/foreword.html).

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

This fourth edition cancels and replaces the third edition (ISO 2360:2003), which has been technically revised.

# Non-conductive coatings on non-magnetic electrically conductive base metals — Measurement of coating thickness — Amplitude-sensitive eddy-current method

## 1 Scope

This document specifies a method for non-destructive measurements of the thickness of non-conductive coatings on non-magnetic electrically conductive base metals, using amplitude-sensitive eddy-current instruments.

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 most oxide coatings produced by anodizing, but is not applicable to all conversion coatings, some of which are too thin to be measured by this method (see [Clause 6](#)).

This method can also be used to measure non-magnetic metallic coatings on non-conductive base materials. However, the phase-sensitive eddy-current method specified in ISO 21968 is particularly usable to this application and can provide thickness results with a higher accuracy (see [Annex A](#)).

This method is not applicable to measure non-magnetic metallic coatings on conductive base metals. The phase-sensitive eddy-current method specified in ISO 21968 is particularly useful for this application. However, in the special case of very thin coatings with a very small conductivity, the amplitude-sensitive eddy-current method can also be used for this application (see [Annex A](#)).

Although the method can be used for measurements of the thickness of coatings on magnetic base metals, its use for this application is not recommended. In such cases, the magnetic method specified in ISO 2178 can be used. Only in case of very thick coatings above approximately 1 mm, the amplitude-sensitive eddy-current method can also be used for this application (see [Annex A](#)).

## 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 and ISO 4618 and the following apply.

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

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

### 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: Adjustment of a measuring system can include zero adjustment, offset adjustment, and span adjustment (sometimes called gain adjustment).

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

Note 3 to entry: After an adjustment of a measuring system, the measuring system must 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”)]

### 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, 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

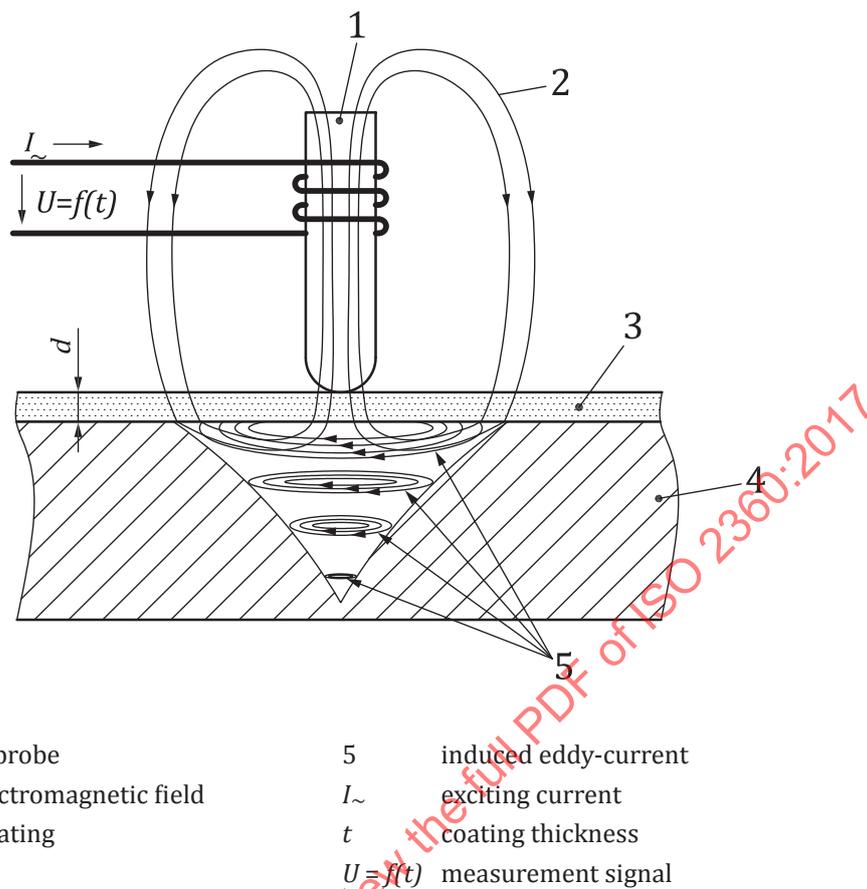
Eddy-current instruments work on the principle that a high frequency electromagnetic field generated by the probe system of the instrument will produce eddy-currents in the base metal beneath the coating on which the probe is placed (see [Figure 1](#)). These induced currents cause a change of the electromagnetic field surrounding the probe coil and therefore result in a change of the amplitude of the probe coil impedance. The induced eddy-current density is a function of the distance between the generating coil and the base metal surface. Consequently, this impedance change 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 amplitude, the test coil is usually part of an oscillator [circuit](#) with a resonant frequency determined by the coil inductance and resistance. A change of the coil impedance amplitude results in a shift of the resonant frequency. Consequently, the measured resonant frequency is a measure of the coating thickness. The values are either pre-processed by digital means or are directly displayed on a usefully scaled gauge.

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	ferrite core of the probe	5	induced eddy-current
2	high frequency electromagnetic field	$I_{\sim}$	exciting current
3	non-conductive coating	$t$	coating thickness
4	base metal	$U=f(t)$	measurement signal

**Figure 1 — Amplitude-sensitive eddy-current method**

## 5 Factors affecting measurement uncertainty

### 5.1 Basic influence of the coating thickness

The sensitivity of a probe, i.e. the measurement effect, decreases with increasing thickness within the measurement range of the probe. In the lower measurement range, this measurement uncertainty (in absolute terms) is constant, independent of the coating thickness. The absolute value of this uncertainty depends on the properties of the probe system and the sample materials, e.g. the homogeneity of the base metal conductivity, the base metal roughness and the sample surface roughness. In the upper measurement range, the uncertainty becomes approximately a constant fraction of the coating thickness.

### 5.2 Electrical properties of the base metal

The conductivity of the base metal determines the induced eddy-current density for a given probe system and frequency. Consequently, the base metal conductivity causes the measurement effect for this method. The relationship between coating thickness and the measured value depends strongly on the conductivity of the base metal. Consequently, 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.

**NOTE** There are instruments and probes available that are capable of automatically compensating the base metal conductivity influence thus avoiding the resulting thickness error.

### 5.3 Geometry: Base metal thickness

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 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 [D.3](#).

However, in the absence of any other information, the required minimum base metal thickness,  $t_{\min}$ , can be estimated from [Formula \(1\)](#).

$$t_{\min} = 3 \cdot \delta_0 \quad (1)$$

where

$\delta_0$  is the standard penetration depth of the base metal (see [A.1](#)).

### 5.4 Geometry: Edge effects

The induction of eddy currents is obstructed by geometric limitations of the base metal (e.g. 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 [D.2](#).

NOTE 2 When compared with the phase-sensitive method of ISO 21968, the amplitude-sensitive eddy-current instruments 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 base metal. 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 base metal 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 base metal surface curvature influence thus avoiding the resulting thickness error.

NOTE 2 A simple experiment to estimate the effect of surface curvature is described in [D.4](#).

### 5.6 Surface roughness

Measurements are influenced by the surface topography of the base metal and the coating. 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 an uncoated base metal with a roughness equivalent to the coated sample base metal.

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

NOTE When compared with the phase-sensitive method of ISO 21968, the amplitude-sensitive eddy-current measurement can be more affected by base metal roughness.

### 5.7 Cleanliness: Lift-off effect

If the probe is not placed directly onto the coating, the gap between the probe and coating (lift-off) will affect the measurement as if it were an additional coating. Lift-off can be produced unintentionally due to the presence of small particles between the probe and coating. The probe tip shall frequently be checked for cleanliness.

### 5.8 Probe pressure

The pressure that the probe exerts on the test specimen can affect instrument reading and shall always be the same during adjustment and measurements.

The influence of the probe pressure is more pronounced in case of soft coatings because the probe tip can be indented into the coating. Therefore, the probe pressure should be as small as possible. Most commercially available instruments are equipped with spring loaded probes, which ensure a constant pressure during the placement. A suitable auxiliary device should be used in case the probe is not spring loaded.

NOTE 1 The contact pressure and the probe tip indentation depth can be reduced by reducing the applied load force or by using a probe with a larger diameter of the probe tip.

NOTE 2 An indentation of the probe tip into soft coatings can be reduced by placing a protective foil with known thickness onto the coated surface. In this case, the coating thickness is the measured thickness minus the foil thickness. This procedure is not applicable when measuring non-magnetic metallic coatings on non-conductive base materials.

### 5.9 Probe tilt

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

The risk of inadvertent tilt can be minimized by the probe design or by the use of a probe-holding jig.

NOTE Most commercially available instruments are equipped with spring loaded probes, which ensure a perpendicular placement on the sample surface.

### 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.

NOTE 1 The influence of temperature variations can be reduced by a temperature compensation of the probe. The manufacturer's specification is taken into account.

NOTE 2 Temperature differences between the probe, electronics of the instrument, environment and sample can cause large thickness errors. One example is the thickness measurement of hot coatings.

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

### 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 base metal. If a difference does exist, then the measurements will, in addition, be affected by an intermediate coating thickness of less than  $t_{\min}$ . If the thickness is greater than  $t_{\min}$ , then the intermediate coating, if non-magnetic, 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. In cases showing 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

Prior to use, every instrument shall be calibrated or adjusted according to the instructions of the manufacturer by means of suitable thickness reference standards and base metal. The material, geometry, and surface properties of the base metal used for calibration or adjustment should be similar to those for 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, standards and base metal 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 has to 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 metals or foils, which are placed onto uncoated base metals.

Foils and coatings shall be non-conductive and non-magnetizable. 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, e.g.  $U$  (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, 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.

In most cases, the foil material is plastic. In contrast to the magnetic method (see ISO 2178), conductive materials, e.g. copper alloys, cannot be used because in such foils, eddy currents can be induced. They would affect the measurement and cause thickness errors.

NOTE When measuring non-magnetic metallic coatings on non-conductive base materials, the situation is "inverted".

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

However, by placing the probe on foils, elastic or plastic deformation may occur, which can affect the measurement result. Moreover, any gap between the pole of the probe, foil and base metal has to be avoided. Especially for concave specimens, or if the foil is wrinkled or bent, the usually low pressure of the spring loaded guiding sleeve of the probe may not be sufficient to ensure there is no gap.

Possible elastic or even plastic deformation of a reference foil depends on the applied force of the probe and the probe tip diameter (see 5.9). Consequently, the calibration of such reference foils should be carried out with comparable values of the applied force and tip diameter to avoid indentation differences during the probe calibration. In this way, respective indentation errors are already taken into account in the foil thickness value, i.e. this value can be smaller than the unaffected geometric thickness. The values of both the applied force and the tip diameter used at the foil calibration should be known from the reference foil manufacturer so that possible thickness errors can be estimated.

### 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. Depending on the instrument types, 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 metal;
- b) a piece of uncoated base metal and a piece of coated base metal with defined coating thickness;
- c) a piece of uncoated base metal and several pieces of coated base metal with defined but different coating thickness;
- d) several pieces of coated base metal with defined but different coating thickness.

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

The stated adjustment methods may lead to different accuracies of the measuring results. Thus, a method that best fits the given application and leads to the desired accuracy should be used. 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 and the better and closer the adjustment points cover the expected thickness interval of the coating to be measured.

NOTE 1 The process that is used to adapt the probe to the given base metal by placing the probe onto the uncoated base metal, 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.

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”.

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 need to be considered in detail, see [Clause 5](#) and [Annex D](#).

NOTE 3 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, e.g. 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) material and geometry of the test specimens are changed, or
- c) other conditions of the inspection have changed (e.g. temperature) whose effects are not known.

As not all changes of measurement conditions and their influences on the measurement accuracy can be immediately recognized (e.g. 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 the 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 (e.g. 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](#) and 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 incorrect uncertainty estimations and consequently in incorrect 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,  $\bar{t}_m$ , 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,  $|\bar{t}_m - t_r|$ , and the combined uncertainty of the calibration measurement. This uncertainty (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.

See [Formulae \(2\)](#) and [\(3\)](#):

$$E = \frac{|t_r - \bar{t}_m|}{2 \times u_{cal}} \quad (2)$$

$$u_{cal} = \sqrt{\left[ t(68,27\%, n-1) \times \frac{s(t_m)}{\sqrt{n}} \right]^2 + [0,5 \times U_r]^2} \quad (3)$$

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  $U_r = \frac{T}{\sqrt{3}}$  and the expanded uncertainty (for 95,4 % confidence level) as  $U_r (k = 2) = 1,653 \times \frac{T}{\sqrt{3}}$ . The deviation from the usual factor 2 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  $t(68,27\%,n-1)$ : 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,  $\bar{t}$ , 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,  $\bar{t}$ , can be estimated by using [Formula \(4\)](#) (Type A):

$$u_{sto} = t(68,27\%,n-1) \times \frac{s(t)}{\sqrt{n}} \quad (4)$$

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, e.g. in case 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 the 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 [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 and 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 properties of the base metal is considered (conductivity variation). As described in [D.5](#), the expected variation should be estimated for the thickness of interest. The resulting thickness variation with respect to the selected reference base metal should be

$\Delta t_{\text{bm}} = \text{abs}(t_{\text{min}} - t_r)$  or  $\Delta t_{\text{bm}} = \text{abs}(t_{\text{max}} - t_r)$ . This gives the standard uncertainty caused by the variation of the base metal properties  $u_{\text{bm}}(k = 1)$  as shown in [Formula \(5\)](#):

$$u_{\text{bm}} = \frac{\Delta t_{\text{bm}}}{\sqrt{3}} \quad (5)$$

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  $\Delta t_{\text{cs}}$  with respect to [D.4](#), the standard uncertainty can be estimated as  $u_{\text{cs}}(k = 1)$  as shown in [Formula \(6\)](#):

$$u_{\text{cs}} = \frac{\Delta t_{\text{cs}}}{\sqrt{3}} \quad (6)$$

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 can be minimized by means of flexible foils as reference standards, e.g. base metal properties ([5.3](#)) or surface curvature ([5.5](#)), if the calibration is carried out with foils on the base metal with identical material and curvature properties as the sample of interest shows. In this case, only 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 1 (see [Annex B](#)). This results in the combined uncertainty,  $u_c$ , as shown in [Formula \(7\)](#):

$$u_c = \sqrt{u_{\text{cal}}^2 + u_{\text{sto}}^2 + u_{\text{bm}}^2 + u_{\text{cs}}^2 + \dots} \quad (7)$$

As the final result, the expanded uncertainty  $U(k = 2)$  is calculated (2-sigma level, 95,45 %) as shown in [Formula \(8\)](#):

$$U(k = 2) = 2u_c \quad (8)$$

And the complete result of the measurement with the thickness value,  $\bar{t}$ , is calculated as shown in [Formula \(9\)](#):

$$t = \bar{t} \pm U(k = 2) \quad (9)$$

## 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](#).

**Table 1 — Repeatability limit ( $r$ )**

Coating thickness	Repeatability limit of first measuring point (triple measurement)	Repeatability limit of all five measuring points
approx. $\mu\text{m}$	$r_{x_1}$ $\mu\text{m}$	$r_{\bar{x}}$ $\mu\text{m}$
12	1,0	1,0
25	1,7	2,3
125	2,7	12,5

### 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](#).

**Table 2 — Reproducibility limit ( $R$ )**

Coating thickness	Reproducibility limit of first measuring point (triple measurement)	Reproducibility limit of all five measuring points
approx. $\mu\text{m}$	$R_{x_1}$ $\mu\text{m}$	$R_{\bar{x}}$ $\mu\text{m}$
12	– <sup>a</sup>	– <sup>a</sup>
25	5,0	5,3
125	6,0	13,0
<sup>a</sup> No calculation of $R_{x_1}$ and $R_{\bar{x}}$ reproducibility could be done in respect of only one sample.		

## 10 Test report

The test report shall include the following information:

- all information necessary for the identification of the test specimen;
  - a reference to this document, including its year of publication, i.e. ISO 2360:2017;
  - the sizes of the test areas over which the measurements were made in square millimetres ( $\text{mm}^2$ );
- NOTE Other units of measurement can be used, with agreement between the supplier and client.
- the location(s) of the test area(s) on each specimen;
  - the number of test specimens measured;
  - an identification of the instrument, probe and standards used for the test, including reference to any validation certification of the equipment;
  - 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;
  - 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) date of the test.

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## Annex A (informative)

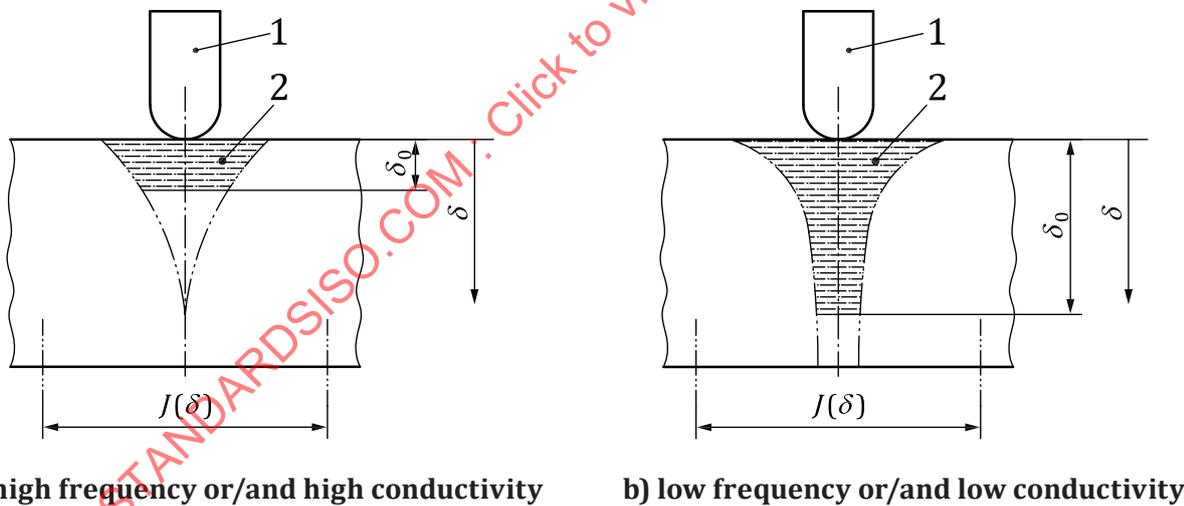
### Eddy-current generation in a metallic conductor

#### A.1 General

Eddy-current instruments work on the principle that a high frequency electromagnetic field generated by the probe system of the instrument produce 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 coating on the conductor (see [A.2](#) and [A.5](#)) or of the conductor itself (see [A.3](#) and [A.4](#)).

The eddy-current generation in a metal conductor is shown in [Figure 1](#).

The eddy-current density,  $J(\delta)$ , changes its magnitude with increasing distance,  $\delta$ , from the surface of the conductor (depth). At the depth,  $\delta_0$  (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 and the permeability and the frequency of the probe coil system; see [Figure A.1](#).



**Key**

- |                 |  |
|-----------------|--|
| 1 probe         | $\delta_0$ standard depth of penetration |
| 2 eddy currents | $\delta$ depth                           |
|                 | $J(\delta)$ density                      |

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

The standard penetration depth,  $\delta_0$ , is a useful value for some important rough estimations. It may be calculated, in mm, using [Formula \(A.1\)](#):

$$\delta_0 = \frac{503}{\sqrt{f \times \sigma \times \mu_r}} \times F_p \quad (\text{A.1})$$

where

$f$  is the probe operating frequency, in Hertz;

$\sigma$  is the electrical conductivity of the conductor, in megasiemens per metre;

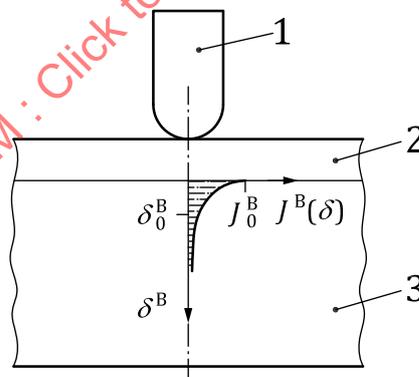
$\mu_r$  is the relative permeability of the conductor (for non-magnetic materials  $\mu_r = 1$ );

$F_p$  is a correction factor determined by the geometry of the probe.

The amplitude-sensitive eddy-current method is best suited to the measurement of non-conductive coatings on non-magnetic base metals (see [A.2](#)) but also to the measurement of bare non-magnetic metallic coatings on non-conductive base metals (see [A.3](#)). The phase-sensitive eddy-current method (see ISO 21968) is best suited to the measurement of non-magnetic metallic coatings on metallic or non-metallic base metals (see [A.2](#) and [A.3](#)) especially if the metallic coating has to be measured through paint or if a contactless measurement is necessary, i.e. a "lift-off" compensation is necessary.

## A.2 Example 1: Non-conductive coating on a conductive 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 coating thickness (see [Figure A.2](#)). A larger coating thickness results in a reduced interaction of the magnetic field of the probe with the base metal and consequently in a reduced eddy-current density. This effect can be used as a measure of the coating thickness.



### Key

- 1 probe
- 2 non-conductive coating
- 3 conductive base metal

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

To establish that the eddy-current density is a unique measure of the coating thickness, this density should not be affected or limited by the base metal thickness. In order to achieve this, the base metal shall be thicker than the minimum base metal thickness. This minimum thickness,  $t_{\min}$ , in mm, can be estimated as shown in [Formula \(A.2\)](#) (see [5.3](#)):

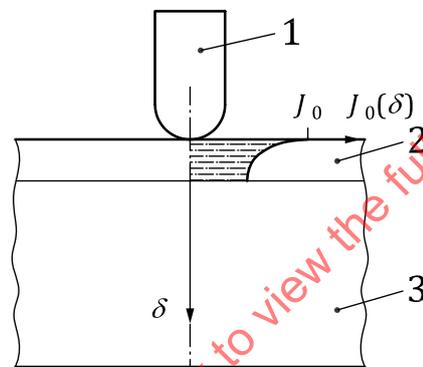
$$t_{\min} = 3\delta_0 \quad (\text{A.2})$$

NOTE  $t_{\min}$  is very often called “saturation thickness”. If the base metal thickness is lower than this minimum thickness,  $t_{\min}$ , the measured value of the coating thickness will be affected and the value of the thickness that is obtained is too high.

However, in the special case of very thin coatings with a very small conductivity, the amplitude-sensitive eddy-current method can also be applied, because this coating is considered as non-conductive. A typical example is thin chromium coating plated on copper with a coating thickness below 10  $\mu\text{m}$ . In this situation, the impact of the eddy currents induced in the coating can be neglected. However, a larger thickness results in an increasing eddy-current density in the coating resulting in an increasing thickness error, although the conductivity of the chromium coating is small. The possible thickness error should be determined or estimated to decide whether this method is applicable or not.

### A.3 Example 2: 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.3](#)). A larger coating thickness results in an increased interaction of the magnetic field of the probe with the conductive coating and consequently in an increased eddy-current density. This effect can be used as a measure of the coating thickness.



**Key**

- 1 probe
- 2 conductive coating
- 3 non-conductive base metal

**Figure A.3 — Schematic of the eddy-current density in the case of conductive coating on a non-conductive material**

The approximate maximum measurable thickness,  $t_{\max}$ , in mm, may be calculated from [Formula \(A.3\)](#):

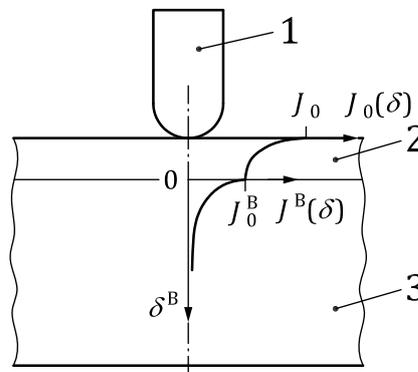
$$t_{\max} = 0,8 \delta_0 \tag{A.3}$$

For example, the thickness range is limited by the penetration depth,  $\delta_0$ . 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 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: Conductive coating on a conductive and/or magnetic base metal

In this case, as shown in [Figure A.4](#), the generated eddy-current density is determined by the thickness and conductivity of the coating and the conductivity and permeability of the base metal. The coating thickness can only be measured by means of the phase-sensitive eddy-current method. Details are given in ISO 21968.



##### Key

- 1 probe
- 2 conductive coating
- 3 conductive base metal

**Figure A.4 — Schematic of the eddy-current density in the case of conductive coating on a conductive and/or magnetic base metal**

#### A.5 Example 4: Non-conductive coating on a 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 coating thickness. (see [Figure A.2](#)). However, the probe impedance is also affected by the magnetic properties of the base metal, resulting in thickness errors. This additional measuring effect is opposite to the effect of the eddy currents. Furthermore, the amplitude-sensitive eddy-current method is very sensitive to changes or fluctuations of the permeability of the base metal, i.e. even when the magnetic base metal was taken into account in the calibration, the thickness results are expected to show strong variations on different magnetic base metals and also at different locations on one base metal (e.g. steel). Consequently, the magnetic method specified in ISO 2178 should be used in this situation.

Only in the case of very thick coatings above approximately 1 mm, the amplitude-sensitive eddy-current method can also be used for this application. There are two reasons for this:

- a) for such thick coatings, the relative impact of the permeability of the base metal is strongly reduced;
- b) in order to measure such thick coatings, the eddy-current probe coil shows a large diameter and consequently, the active area of the coating included in the measurement is increased. In this way, the probe integrates variations of the permeability over the entire active area, resulting in more stable results.

The minimum thickness of the coating necessary to use this method for these applications should be determined with respect to the expected acceptable repeatability and trueness of the measurement.

## 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.

On the basis of 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 in [Formula \(B.1\)](#):

$$t = F(H_0, H_1, H_2, \dots, H_i, \dots, H_n) \quad (\text{B.1})$$

To every influence quantity belongs a sensitivity coefficient,  $c_i$ , which indicates how strong a modification  $\Delta H_i$  affects the result  $t$ .

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

$$c_i = \frac{\delta t}{\delta H_i} \quad (\text{B.2})$$

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 [Formula \(B.3\)](#) and [Formula \(B.4\)](#):

$$u_{\text{sto}} = t(68,27\%, n-1) \times \frac{s(t)}{\sqrt{n}} \quad (\text{B.3})$$

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

where

$s$  is the empirical standard deviation of the repetition measurement  $n$ , and  
 $t(68,27\%, n-1)$  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](#).

### B.3 Type B

Many influencing factors or errors are not to be described by Type A, e.g. 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, the ad hoc probability factors are allocated. In many practical cases, the influencing factors treated here are to be described by a uniform distribution (rectangle distribution).

If an influence quantity fluctuates within a section  $\Delta H_i$ , the resulting uncertainty can be calculated as shown in [Formula \(B.5\)](#):

$$u_B = \frac{|t_{\max} - t_{\min}|}{\sqrt{12}} \quad (\text{B.5})$$

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, e.g. for  $U(k = 2)$ , follow the standard uncertainty shown in [Formula \(B.6\)](#):

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

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 are equally one; see [Formula \(B.7\)](#):

$$u = \sqrt{\sum_i (c_i u_i)^2} \quad (\text{B.7})$$

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 \(B.8\)](#):

$$U = k \cdot u \quad (\text{B.8})$$

## Annex C (informative)

### Basic performance requirements for coating thickness gauges which are based on the amplitude-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) principle of measurement;
- b) measuring range;
- c) basic information on measuring uncertainty or 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, curvature and thickness of the base metal and by the edge effect (measurements close to an edge);
- e) battery operating time;
- f) function of an undervoltage monitor and automatic undervoltage switch-off;
- g) permissible operating temperature;
- h) permissible storage temperature;
- i) available methods for calibration and adjustment;
- j) contact force of probes with spring loaded guiding sleeves;
- k) availability of temperature compensation;
- l) measuring rate;
- m) data memory (design, capacity, data communication);
- n) size and weight of 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 by using a plane and uncoated base metal and a representative number of coated calibration standards or calibration foils, whose 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 shall 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.

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## 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, consists of using a clean, uncoated and even sample of the base metal and follows the procedure described in Step 1 to Step 4 below. The procedure is illustrated in [Figure D.1](#).

##### Step 1

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

##### Step 2

Adjust the instrument to read zero.

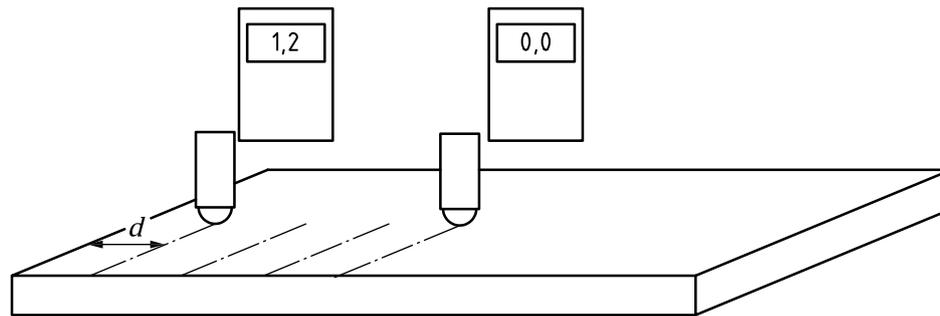
##### Step 3

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 tolerance.

##### 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 further from the edge than the distance 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

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

#### 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](#)).

#### Step 2

Adjust the instrument to read zero.

#### 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,  $t_0^{\text{crit}}$ , and no additional uncertainty needs to be considered. If the instrument reading changes negatively with respect to the expected uncertainty,  $t_0$  is smaller than  $t_0^{\text{crit}}$ , i.e. the measurement is affected by the too small base metal thickness.

#### Step 4

If  $t_0$  is smaller than  $t_0^{\text{crit}}$ , 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  $t_0 < t_0^{\text{crit}} < 2t_0$ . If the instrument reading shows a larger negative value than in Step 3, then two times of  $t_0$  is still smaller than  $t_0^{\text{crit}}$ . Continue to stack further samples in order to estimate  $t_0^{\text{crit}}$ .

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

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

In order to improve the accuracy of the estimation of  $t_0^{\text{crit}}$ , 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.

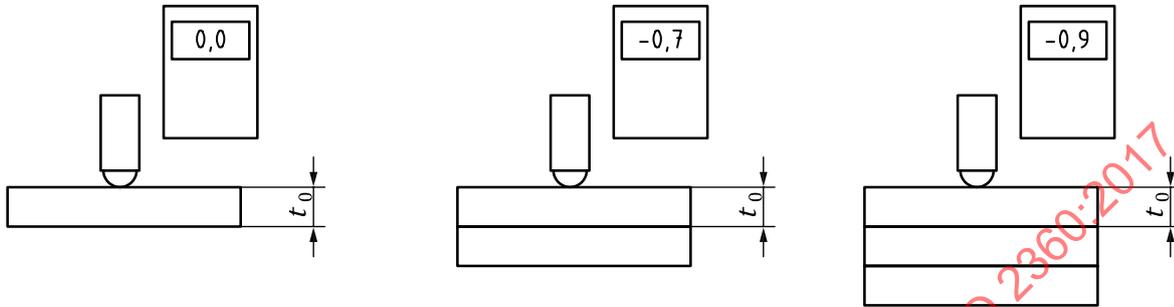


Figure D.2 — Schematic representation of the test for base metal thickness

#### 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 Step 1 to Step 4 below. All used samples should provide the same material properties as the base metal. The procedure is illustrated in Figure D.3 using the example of a convex curvature.

##### 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).

##### Step 2

Adjust the instrument to read zero.

##### Step 3

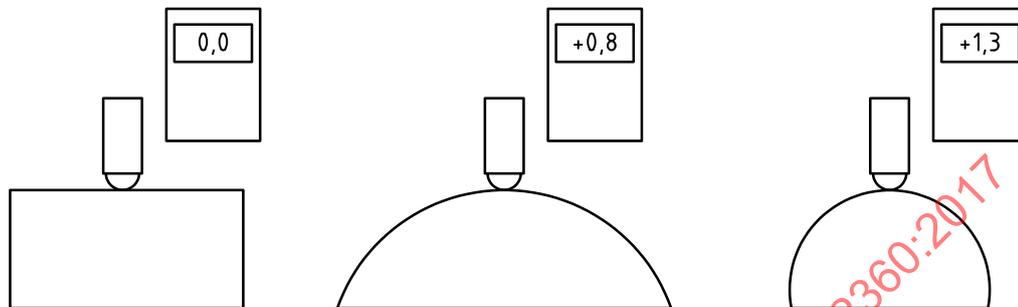
Place the probe on each sample starting with the largest available diameter and then continue the test with decreasing sample diameters. Note the diameter where a change of the instrument reading (positive increase) occurs with respect to the expected uncertainty or to the given thickness tolerance.

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 distance can 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 (e.g. 10 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 of the base metal

In practical situations, the conductivity of the base metal varies very often. A simplified procedure described in Step 1 to Step 5 below helps to reduce this influence and 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](#).

### 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](#)).

### Step 2

Adjust the instrument to read zero.

### 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.

### Step 4

Calculate the average of the readings of all samples and select the sample with the smallest deviation from this average.

### 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.

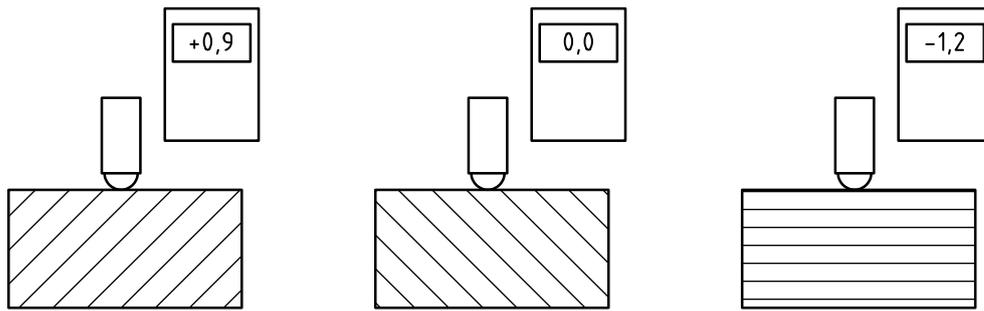


Figure D.4 — Schematic representation of the test for base metal conductivity test

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## Annex E (informative)

### Table of the student factor

Table E.1 — Student factor

Number of measurements <i>n</i>	Fraction <i>p</i> in percent	
	68,27 %	95,45 %
2	1,84	13,97
3	1,32	4,53
4	1,20	3,31
5	1,14	2,87
6	1,11	2,65
7	1,09	2,52
8	1,08	2,43
9	1,07	2,37
10	1,06	2,32
11	1,05	2,28
12	1,05	2,25
13	1,04	2,23
14	1,04	2,21
15	1,04	2,20
16	1,03	2,18
17	1,03	2,17
18	1,03	2,16
19	1,03	2,15
20	1,03	2,14
∞	1,00	2,00

## Annex F (informative)

### Example of uncertainty estimation (see [Clause 8](#))

#### F.1 Sample details

The example sample to be measured is as follows:

- paint/aluminium (part of a car body);
- expected thickness: around 25  $\mu\text{m}$ ;
- the base metal is not accessible, but possible thickness variations caused by the used aluminium lots (conductivity variations) have been determined by an experiment (see [D.5](#)): measurement of uncoated aluminium parts from car body production representing the variability of used aluminium from different suppliers, production lots etc., resulting complete thickness variation range at  $t = 25\mu\text{m}$ :  $\Delta t_{\text{bm}} = \pm 1,2\mu\text{m}$

#### F.2 Steps

**F.2.1** The example sample is measured by following these steps.

a) Verify the probe calibration:

- 1) 10 repeated measurements with a reference foil of  $t_r = 25,2\mu\text{m}$  on base metal (including zeroing on base metal)
- 2) The given tolerance of the reference foil:  $T = \pm 0,5\mu\text{m}$ .
- 3) The used base metal is a selected reference base metal (see [D.5](#)).
- 4) The result is ( $n=10$ ):  $\bar{t} = 24,06\mu\text{m}$  and  $s(t) = 0,11\mu\text{m}$ .
- 5) Calculate the uncertainty and  $E$  (see [8.2](#)):

i) The standard uncertainty of the reference foil is:

$$u_r = \frac{T}{\sqrt{3}} = \frac{0,5\mu\text{m}}{\sqrt{3}} = 0,29\mu\text{m}$$

ii) The standard uncertainty of the verification measurement (only the stochastic component is considered) is:

$$u_{\text{sto}} = t(68,27\%, n-1) \times \frac{s(t)}{\sqrt{n}} = 1,06 \times \frac{0,11\mu\text{m}}{\sqrt{10}} = 0,04\mu\text{m}$$

iii) The combined uncertainty is  $u_c = \sqrt{(0,04\mu\text{m})^2 + (0,29\mu\text{m})^2} = 0,29\mu\text{m}$

iv) The expanded uncertainty is  $U_{\text{cal}}(k=2) = 2 \times u_c = 0,58\mu\text{m}$

v) The result is  $E = \frac{|\bar{t} - t_r|}{U_{\text{cal}}(k=2)} = \frac{1,14\mu\text{m}}{0,58\mu\text{m}} = 1,96$