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Paints and varnishes — Wedge-cut method for determination of film thickness (scribe and drill method)

Peintures et vernis — Détermination de l'épaisseur par la méthode d'entaille en coin (Méthode de rayer et de forage)

Reference number
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Foreword

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The committee responsible for this document is ISO/TC 35, *Paints and varnishes*, Subcommittee SC 9, *General test methods for paints and varnishes*.

Paints and varnishes — Wedge-cut method for determination of film thickness (scribe and drill method)

1 Scope

This International Standard specifies a destructive method for determination of the dry film thickness, in which damage to the coat caused in a definite manner is evaluated microscopically. The method is suitable for almost all coat-substrate combinations and also allows determination of the single film thicknesses of coating systems.

The method cannot be applied or can only be applied with restrictions in case of

— too soft and/or elastic coatings (no recognizable scribe or drill hole can be observed),

— hard (cannot be scribed/drilled) or too soft and/or elastic substrates,

— too low visual contrast between the coating and substrate, and

— film thicknesses that are larger than the depth of field of the measuring microscope.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

3 Terms and definitions

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

3.1
substrate
surface to which a coating material is applied or is to be applied

[SOURCE: ISO 4618:2014, 2.244]

3.2
coating
layer formed from a single or multiple application of a coating material to a substrate

[SOURCE: ISO 4618:2014, 2.50.1]

3.3
coating system
combination of all coats of coating materials which are to be applied or which have been applied to a substrate

Note 1 to entry: The actual coating system can be characterized by the number of coats involved.

Note 2 to entry: See also *coating* (3.2).

[SOURCE: ISO 4618:2014, 2.54]

3.4
single coat
part of a coating system

3.5
total film thickness
distance between the surface of the coating and surface of the substrate

3.6
single film thickness
distance between the surface of a single coat and the surface of the coat (substrate) underneath

3.7
dry-film thickness
thickness of a coating remaining on the surface when the coating has hardened

[SOURCE: ISO 2808:2007, 3.5]

3.8
wedge cut
damage to the coating system caused mechanically under the specified angle to the surface and extending into the substrate

Note 1 to entry: The wedge cut can be implemented as a linear scribe or as a conical bore hole.

3.9
wedge-cut image
microscopic image of a wedge cut

3.10
adhesive failure
detachment of a coating from the substrate caused by external forces

Note 1 to entry: The substrate can be another coating beneath or the basic material.

3.11
cohesion failure
loss of cohesion within a coating caused by external forces

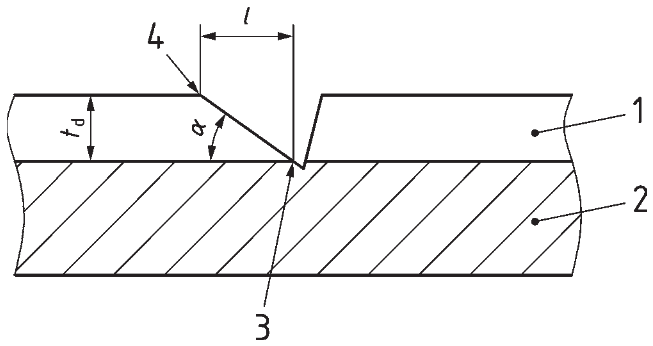
4 Principle

A wedge cut with a known flank angle is made in the coating using a scribing or drilling tool. The film thickness is calculated from the width of the flank projection of the wedge cut obtained with the measuring microscope.

5 Wedge-cut principle

The wedge cut for determination of the film thickness according to this International Standard can be made using a scribing tool (method A) or a drilling tool (method B).

Figure 1 shows a wedge cut according to method A in the cross section. The basis length, *l*, is the projection of the wedge-cut flank within the coating and is measured with a microscope between the upper and lower contrast mark in micrometres.



Key

1 coating
2 substrate
3 lower contrast mark (intersection from the substrate to the coating)
4 upper contrast mark
l wedge-cut basis
t_d dry-film thickness
α wedge-cut angle

Figure 1 — Wedge cut according to method A (single coat/cross section)

The film thickness is determined according to Formula (1):

$$t_d = l \cdot \tan \alpha \qquad (1)$$

where

t_d is the dry-film thickness, in micrometres;

l is the wedge-cut base (microscope reading), in micrometres;

$\tan \alpha$ is the wedge-cut factor of the wedge-cut tool used.

NOTE 1 Instruments are available where the microscope reading is indicated in “number of scale divisions” and the wedge-cut factor in “micrometres per scale division”.

NOTE 2 Instruments are available where the microscope reading (in micrometres) for calculating the film thickness is divided by a divisor assigned to the wedge-cut tool.

The film thickness measuring range is as follows:

— determined by the wedge-cut angle, the dimensions of the wedge-cut tool and the scale measuring range of the microscope;

— limited by the depth of field of the measuring microscope (see A.9).

The resolution of the dry-film thickness measurement is determined by the wedge-cut angle and the scale division of the measuring microscope.

EXAMPLE For the usual wedge-cut angles α = 5,7° and α = 14,0°, the following is indicated in Table 1:

— the wedge-cut factor $\tan \alpha$;

— the dry-film thickness measuring range (= scale measuring range × $\tan \alpha$);

— the absolute dry-film thickness resolution Δ_a (= scale division × $\tan \alpha$);

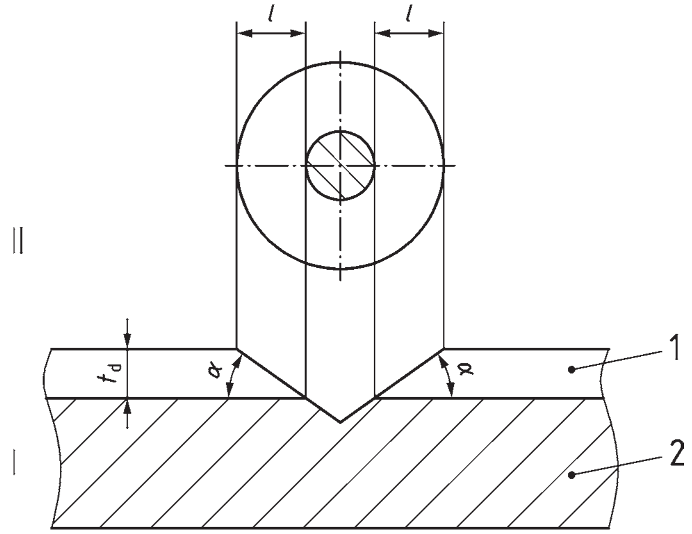
— the relative dry-film thickness resolution Δ_r (= $(\Delta_a/t_d) \times 100$; t_d = dry-film thickness).

In the above, it is assumed that the measuring microscope has a scale measuring range of 2 mm, as well as a scale division of 0,02 mm and that the wedge-cut tool is sufficiently dimensioned.

Table 1 — Numerical data on the wedge-cut method

Wedge-cut angle α	°	5,7	14,0
Wedge-cut factor tan α		0,10	0,25
Film thickness measuring range	µm	up to 200	up to 500
Absolute film thickness resolution Δ_a	µm	2	5
Relative film thickness resolution Δ_r	%	$200/t_d$	$500/t_d$

Figure 2 shows a wedge cut according to method B in the cross section (I) and the associated wedge-cut image (II) visible through the microscope. Here, the section *l* to be measured with the microscope is the distance between the concentric circles.



Key

1 cross section

2 wedge-cut image

I coating

II substrate

l wedge-cut basis

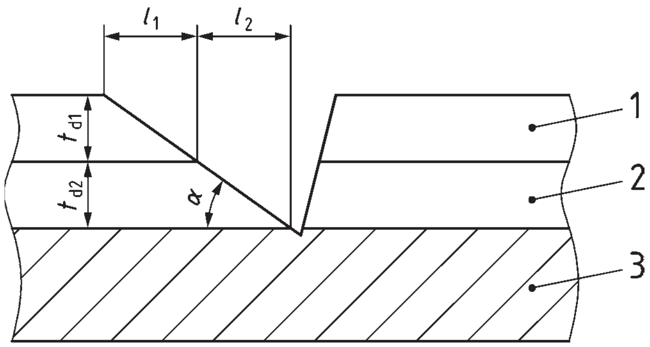
t_d dry-film thickness

α wedge-cut angle

Figure 2 — Wedge cut according to method B (single coat)

In the case of coating systems, the single film thicknesses can be determined in a similar manner.

Figure 3 shows the wedge-cut scribe (method A) for a 2-coat system. The single dry-film thicknesses t_{d1} and t_{d2} are then calculated from the microscope readings l_1 and l_2 with Formula (1) for $t_{d1} = l_1 \cdot \tan \alpha$ and $t_{d2} = l_2 \cdot \tan \alpha$.



Key

1 single coat 1

2 single coat 2

3 substrate

l_i wedge-cut basis associated with t_{di} (i = 1, 2)

t_{di} dry-film thickness of the single coat i (i = 1, 2)

α wedge-cut angle

Figure 3 — Wedge cut according to method A (2-coat system/cross section)

6 Apparatus

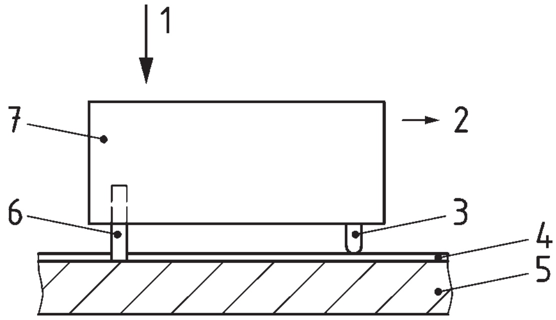
6.1 Method A

6.1.1 Wedge-cut scribing device, as shown schematically in Figure 4, with the following features.

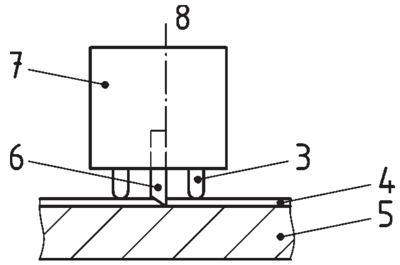
6.1.1.1 The stylus 6 is fastened interchangeably in the metal block 7 and protrudes as far out as the support bolts 3.

NOTE There are wedge-cut scribing devices that are equipped with support wheels instead of the support bolts.

6.1.1.2 The device shall be adjusted so that, when placed on an even surface, the stylus axis 8 is oriented vertically to this surface.



a) Side view



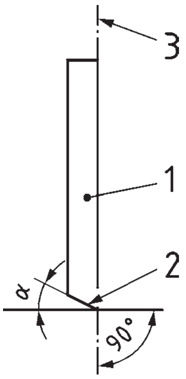
b) Front view

Key

1 direction of load
2 direction of scribing
3 support bolts
4 coating
5 substrate
6 wedge-cut stylus
7 metal block
8 stylus axis

Figure 4 — Wedge-cut scribing device

6.1.2 Wedge-cut stylus, made from hard metal with a form according to Figure 5, with indication of the wedge-cut factor and/or the wedge-cut angle.



Key

1 shaft
2 cutting edge
3 stylus axis
α wedge-cut angle

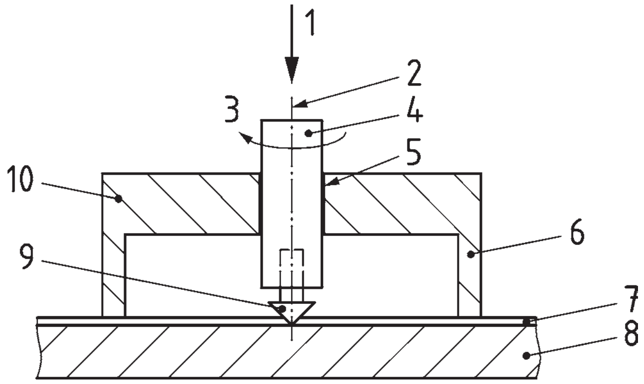
Figure 5 — Wedge-cut stylus

6.2 Method B

6.2.1 Wedge-cut drilling device, as shown schematically in Figure 6, with the following features.

6.2.1.1 The rotational movement of the drill bit 9 fastened interchangeably in the drilling spindle 4 (see Figure 6) may be generated manually or by an electromotive drive.

6.2.1.2 The device shall be adjusted so that, when placed on an even surface, the drill axis 2 is oriented vertically to this surface.

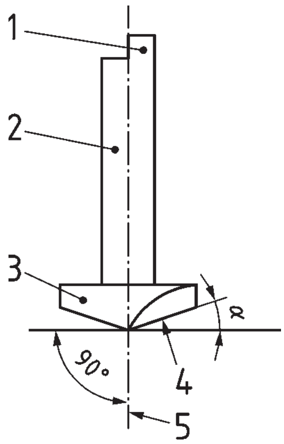


Key

1	direction of load	6	support
2	drill axis	7	coating
3	rotational movement	8	substrate
4	drilling spindle with chuck	9	wedge-cut drill bit
5	drilling spindle guide	10	housing

Figure 6 — Wedge-cut drilling device

6.2.2 Wedge-cut drill bit, made from hard metal with a form according to Figure 7, with indication of the wedge-cut factor and/or the wedge-cut angle.



Key

1	coupling	4	cutting edge
2	shaft	5	drill axis
3	drill head	α	wedge-cut angle

Figure 7 — Wedge-cut drill

6.3 Measuring microscope

Measuring microscope, with illumination device and with

— a minimum of 40x magnification,

— a measuring range of minimum 2 mm, and

— a scale division of maximum 0,02 mm.

NOTE 1 Standard wedge-cut devices are equipped with an integral measuring microscope and an integral illumination device.

NOTE 2 Instead of a conventional measuring microscope, a video microscope can be used and the wedge-cut image evaluated digitally.

7 Test specimens

The specimens shall exhibit a planar area, which is at least twice as big as the base plane of the wedge-cut device.

NOTE 1 Clamping devices are available for wedge-cut drilling devices (method B), which also enable measurements on specimens with a very small planar area (typical dimensions: 15 mm × 15 mm). Specimens with complex geometry (e.g. profiles) can also be fastened with these devices for measuring the dry-film thickness of such specimens.

NOTE 2 Under certain boundary conditions, film thickness determinations on curved specimens are also possible (see Annex C).

8 Procedure

8.1 Sample preparation

A laminar contrast marking should preferably be applied to the coating in the area in which the wedge-cut is to be made, so as to make the microscopic measurement easier.

A black permanent felt-tip pen is normally used for bright coatings. A white or silver-coloured paint felt-tip pen may be used for dark specimens. In this case, the marking coat shall be applied thinly and shall be fully hardened before making the wedge cut. It shall be ensured that the solvent in the felt-tip pen does not attack the coating.

8.2 Number of determinations

For each determination of the dry-film thickness, three wedge-cut scribes or wedge-cut drills, respectively, shall be applied on the test panel. The wedge-cut basis, l, shall be measured for each cut or each drill at two different test points.

8.3 Method A (wedge-cut scribe)

8.3.1 Insert the wedge-cut stylus (6.1.2) for the intended measuring range according to 6.1.1.1 into the wedge-cut scribing device (6.1.1) and fix.

8.3.2 Place the scribing device on the coating and pull with a speed of about 10 mm/s over a section of minimum 10 mm (see Key 2 in Figure 4). When doing so, press down the scribing device so that a scribe is made down into the substrate.

8.3.3 Place the measuring microscope (6.3) on the coating and measure the width of the projection of the wedge-cut flank from the surface (marking) to the substrate (see Figure 1) transverse to the wedge-cut scribe at two points of the scribe.

8.3.4 Use the measured values and the wedge-cut factor of the stylus to calculate the dry-film thicknesses, in micrometres, according to Formula (1).

8.3.5 Repeat implementation steps 8.3.2 to 8.3.4 at two further points on the specimen.

8.3.6 As a result, indicate the mean value, in micrometres, from the six determinations.

8.3.7 To determine the single-dry-film thicknesses of a coating systems, proceed analogously and according to Clause 5.

8.4 Method B (wedge-cut bore)

8.4.1 Insert the wedge-cut drill bit (6.2.2) for the intended measuring range into the wedge-cut drilling device (6.2.1) and fix.

8.4.2 Place the drilling device on the coating and lower the rotating drill bit onto the coating. When doing so, load the drilling spindle axially (see Key 1 in Figure 6) so that the coating is drilled conically down into the substrate.

8.4.3 Place the measuring microscope (6.3) on the coating and measure the width of the projection of the wedge-cut flank from the surface (marking) to the substrate (see Figure 2) in a radial direction at two points of the drill bore cone.

8.4.4 Use the measured values and the wedge-cut factor of the drill bit to calculate the dry-film thicknesses, in micrometres, according to Formula (1).

8.4.5 Repeat implementation steps 8.3.2 to 8.3.4 at two further points on the specimen.

8.4.6 As a result, indicate the mean value, in micrometres, from the six determinations.

8.4.7 To determine the single-dry-film thicknesses of a coating system, proceed analogously and according to Clause 5.

9 Precision

Precision data are currently not available.

10 Test report

The test report shall contain at least the following data:

a) all individual details required for identification and characterization of the specimen, i.e. data

   1) concerning the coating (manufacturer, product identification, batch number, application method, drying/hardening conditions, aging/conditioning conditions, etc.), and

   2) concerning the substrate (material, thickness, form, dimensions, curvature, etc.);

b) a reference to this International Standard, i.e. ISO 19399;

c) the method used (A or B);

d) the wedge-cut tool used (wedge-cut factor/wedge-cut angle);

e) the test results according to 8.3.6, 8.3.7, 8.4.6, or 8.4.7: the dry-film thickness and, if applicable, the single-dry-film thicknesses, in micrometres;

f) any deviation from the specified test method;

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

h) the name of the inspector and test laboratory;

i) the date of the test.

Annex A
(informative)

Error sources and measuring problems

A.1 Soft and/or elastic coating

A.1.1 Phenomenon

Three negative effects can occur in the case of coatings that are too soft and/or too elastic.

— Non-separated cuttings adhering to the wedge cut comprising coating material impair the wedge-cut image (at least one of the contrast marks not clearly distinct).

— The effective wedge-cut angle is greater than the specified nominal wedge-cut angle due to spring back of the elastic coating after the scribing/drilling.

— A bulge can be caused at the upper edge of the wedge cut due to plastic deformation of the soft coating.

A.1.2 Effect

A correct evaluation is not possible in the case of unclearly distinct contrast marks and upon bulge formation. The dry-film thickness can only be estimated roughly at best.

In the case of an elastic spring back of the coating, too small dry-film thickness values are determined systematically.

A.1.3 Remedy

In some cases, the mechanical properties of the coating can be optimized by cooling (freezer or cold spray). The coating surface shall be protected against solvent attack with an aluminium foil when using cold spray.

In order to avoid the formation of no separated cuttings from coating material, drilling should always be conducted intermittently, i.e. not in one go, in the case of method B. Blow off the drill cuttings between the drilling strokes.

A.2 Soft and/or elastic substrate

A.2.1 Phenomenon

Four negative effects can occur in the case of substrates that are too soft and/or too elastic.

— The lower contrast mark is unclearly distinct due to non-separated substrate cuttings adhering to the wedge cut.

— Long substrate cuttings can cause a coat disbonding in case of tough substrate material (see A.4).

— Spring back of the elastic substrate after scribing/drilling impairs the distinctness of the lower contrast mark.

— A bulge can be caused at the upper edge of the substrate cone due to plastic deformation of the soft substrate.

A.2.2 Effect

A correct evaluation is not possible in the case of unclearly distinct contrast marks and upon bulge formation. The dry-film thickness can only be estimated roughly at best.

A.2.3 Remedy

In the case of plastic substrates, the mechanical properties can be optimized by cooling (freezer or cold spray) in some cases. The coating surface shall be protected against solvent attack with an aluminium foil if using cold spray.

In order to avoid the formation of non-separated substrate cuttings, drilling should always be conducted intermittently, i.e. not in one go and as deep into the substrate as possible in the case of method B. Blow off the drill cuttings between the drilling strokes.

A.3 Hard substrate (that cannot be scribed/drilled)

A.3.1 Phenomenon

In the case of very hard substrate materials (e.g. concrete), the wedge cut cannot be made fully (i.e. not into the substrate), with the result that the lower contrast mark is absent or only recognizable indistinctly in the wedge-cut image.

A.3.2 Effect

The wedge cut cannot be evaluated correctly. Only a lower limit can be indicated for the dry-film thickness at best.

A.3.3 Remedy

Method A: There is no technical solution for the measuring problem.

Method B: The wedge-cut basis, l, can be determined by measuring the entire drill bore cone diameter and dividing this by two. If the scale measuring range of the microscope is not adequate for this, a drill bit with a larger wedge-cut angle (but also with lower dry-film thickness resolution) shall be used.

A.4 Wedge-cut with adhesive failure

A.4.1 Phenomenon

The lower part of the wedge-cut flank has broken off due to disbonding. The disbonding is frequently caused by the formation of long substrate cuttings in the case of substrate materials that are too tough.

A.4.2 Effect

The ascertained dry-film thickness values are systematically too small. Only a lower limit can be indicated for the dry-film thickness.

A.4.3 Remedy

The disbonding effect is particularly drastic if the wedge-cut tool penetrates the limit between the coating and substrate. Scribing/drilling should therefore be performed as deeply as possible into the substrate.

The measures described in A.2 can be helpful if the plastic substrate is tough: Cooling the specimen, as well as intermittent drilling and blowing the cuttings away, if method B is used.

In the case of method B, the edge of the drill bore cone can still be visible in the substrate, although the coating is absent there. This shall then be used as the lower contrast mark during microscopic measuring.

A.5 Wedge-cut with cohesive failure

A.5.1 Phenomenon

Parts of the coating have broken off in the upper area of the wedge-cut flank.

A.5.2 Effect

The ascertained film thickness values are systematically too small. Only a lower limit can be indicated for the dry-film thickness.

A.5.3 Remedy

The breaking off of the coating can only be prevented by careful scribing/drilling.

A.6 Insufficient visual contrast

A.6.1 Phenomenon

The colour/brightness difference between the coating and the substrate or between the single coats of a coating system is so low that no contrast marks or only unclear contrast marks are recognizable in the wedge-cut image.

A.6.2 Effect

The wedge cut cannot be evaluated correctly. The dry-film thickness can only be estimated roughly at best.

A.6.3 Remedy

The problem can be solved in some cases by

— using a high-quality stereo measuring microscope,

— optimizing the illumination equipment (light intensity, lighting geometry, etc.),

— utilizing a metamerism effect (adapted illuminant, monochromatic LED light, etc.),

— using a fluorescence microscope, and

— use of a contrast medium (see also the note in 8.1).

A.7 Surface curvature

A.7.1 Phenomenon

The curvature of the specimen surface causes a distortion of the wedge-cut geometry (see Figure C.1). In addition, it is not always ensured that the axis of the wedge-cut tool is oriented vertically to the coating surface (see A.8).

A.7.2 Effect

If no further complication (e.g. specimen tilting, see A.8) is superimposed with the influence of the curvature, the film thickness values calculated with Formula (1) are systematically too small (too large) in the case of convex (concave) curvature (see Annex C).

A.7.3 Remedy

The problem can only be solved if using method B: If it is ensured (e.g. by a special device) that the drill axis is oriented vertically to the specimen surface in the area of the wedge cut and the curvature radius is known, the effect of the curvature can be corrected (see Annex C).

On the other hand, the results of Annex C also provide the option of estimating the minimum permissible curvature radius for a specified maximum error, for which the standard evaluation with Formula (1) is still adequate. This applies for both methods (A and B).

A.8 Specimen tilting

A.8.1 Phenomenon

In the case of measurements on non-planar specimens, the specimen normal (see Figure B.2) can be tilted against the axis of the wedge-cut tool.

A.8.2 Effect

Method A: The tilt effect cannot be seen from the wedge-cut image. The evaluation reveals, depending on the direction of the tilt, dry-film thickness values that are systematically too small or too large.

Method B: The tilt effect is clearly discernible in the wedge-cut image, as ellipses inside one another are visible instead of concentric circles (see Figure B.1).

A.8.3 Remedy

Method A: The systematic error caused by the tilt cannot be corrected, as it is not recognized.

Method B: Two measuring values can be read off from the ellipsis constellation (see Figure B.1), which enable calculation of the film thickness (see Annex B).

NOTE The dry-film thickness can only be determined if the tilt angle is less than the wedge-cut angle.

A.9 Film thickness greater than the depth of field of the measuring microscope

A.9.1 Phenomenon

If the dry-film thickness is greater than the depth of field of the measuring microscope, both contrast marks cannot be brought into focus simultaneously during the microscopic measurement.

NOTE 1 The depth of field of the 50x magnification microscope usually supplied with the wedge-cut device is about 500 µm.

NOTE 2 If the scale reading is performed with focused contrast marks in succession, it cannot be ruled out that the optical axis of the microscope moves relative to the specimen and hence, the wedge-cut image relative to the scale.

A.9.2 Effect

The dry-film thickness can only be determined with a large error or not at all.

A.9.3 Remedy

To measure the wedge cut, clamp the specimen firmly and

— use a high-quality laboratory microscope with sufficient depth of field and/or precise vertical drive, or

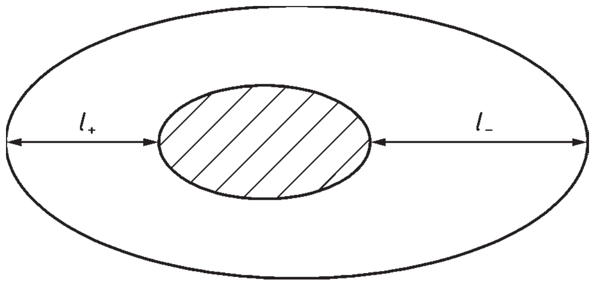
— use a video microscope.

Annex B
(informative)

Evaluation with tilted specimen

B.1 Basic principles

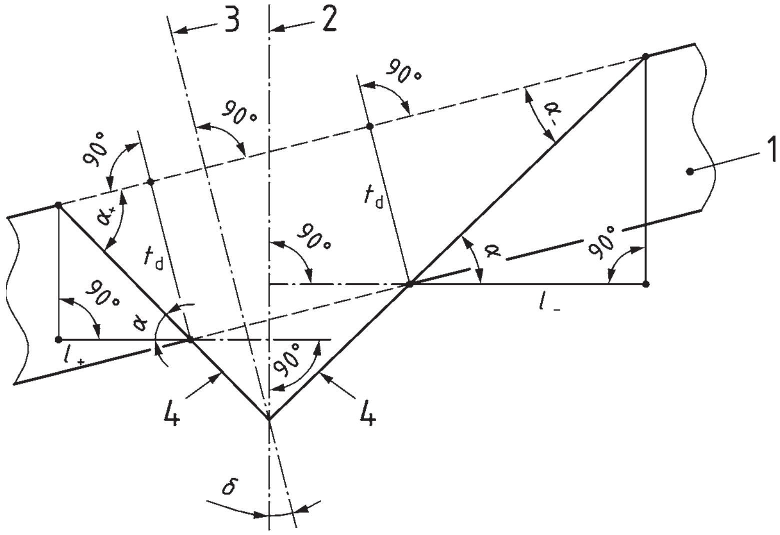
In the case of a tilted specimen, the specimen normal is tilted by a tilt angle, δ, against the axis of the wedge-cut tool and a wedge-cut image according to Figure B.1 is obtained when using drilling method B. The geometrical details are shown in Figure B.2.



Key

$l_\pm$ measuring section

Figure B.1 — Wedge-cut image with tilted specimen (method B)



Key

1 coating

2 drill axis

3 normal of the specimen

4 wedge-cut flank (bore cone)

$l_{\pm}$ measuring section (see Figure B.1)

t_d dry-film thickness

α wedge-cut angle

$\alpha_{\pm}$ derived angle: $\alpha_{\pm} = \alpha \pm \delta$

δ tilt angle

Figure B.2 — Geometrical details of a wedge cut with tilted specimen (method B)

The wedge-cut image B.1 allows the measuring variables, l_- and l_+, to be read off, in micrometres and for the film thickness t_d, in micrometres, the following applies according to Figure B.2:

$$t_d = l_{\pm} \frac{\sin\left(\alpha + \delta\right)}{\cos \alpha} \quad \text{(B.1)}$$

NOTE For the derivation of Formula (B.1), the sections $l_{\pm}$ are firstly projected onto the wedge-cut flank 4 [multiplication by (1/cos α)] and then onto a normal of the specimen parallel to 3 [multiplication by cos (90° – $\alpha_{\pm}$) = sin $\alpha_{\pm}$] (see Figure B.2).

As the tilt angle δ is unknown, the film thickness cannot be calculated directly.

B.2 Calculation of the tilt angle

Based on Formula (B.1) the following is obtained

$$\frac{l_-}{l_+} = \frac{\sin(\alpha + \delta)}{\sin(\alpha - \delta)} = \frac{\sin\alpha \cdot \cos\delta + \sin\delta \cdot \cos\alpha}{\sin\alpha \cdot \cos\delta - \sin\delta \cdot \cos\alpha} = \frac{1 + \tan\delta \,/\, \tan\alpha}{1 - \tan\delta \,/\, \tan\alpha} \tag{B.2}$$

and after algebraic transformation

$$\tan\delta = \frac{l_- / l_+ - 1}{l_- / l_+ + 1} \cdot \tan\alpha \tag{B.3}$$

This yields

$$\delta = \tan^{-1}\left(\frac{l_- - l_+}{l_- + l_+} \cdot \tan\alpha\right) \tag{B.4}$$

The film thickness can be calculated with this using Formulae (B.1) with l_- or l_+.

B.3 Approximation for small tilt angle

The approach to calculate the film thickness approximately from the determined measuring values according to

$$\overline{t_\mathrm{d}} = \frac{l_- + l_+}{2} \cdot \tan\alpha \tag{B.5}$$

can only be applied in the case of very small tilt angles (see Table B.1). A generally valid approximation shall therefore be derived imperatively on the basis of Formula (B.1):

The factor sin $(\alpha \pm \delta)$/cos α contained in Formula (B.1) can be transformed for small tilt angles (i.e. $\cos\delta \approx 1$ and $\sin\delta \approx \tan\delta$) into

$$\frac{\sin(\alpha \pm \delta)}{\cos\alpha} = \frac{\sin\alpha \cdot \cos\delta \pm \sin\delta \cdot \cos\alpha}{\cos\alpha} = \tan\alpha \cdot \cos\delta \pm \sin\delta \approx \tan\alpha \pm \tan\delta \tag{B.6}$$

giving us by using $\tan\delta$ according to Formula (B.3):

$$\frac{\sin(\alpha \pm \delta)}{\cos\alpha} \approx \left(1 \pm \frac{l_- - l_+}{l_- + l_+}\right) \cdot \tan\alpha = \frac{2 \cdot l_\mp}{l_- + l_+} \cdot \tan\alpha = \frac{2}{l_\pm} \cdot \frac{l_- \cdot l_+}{l_- + l_+} \cdot \tan\alpha \tag{B.7}$$

Using Formulae (B.1) and (B.7), the approximate value $t_{\mathrm{d,\,apr}}$ for the film thickness is

$$t_{\mathrm{d,\,apr}} = 2 \cdot \frac{l_- \cdot l_+}{l_- + l_+} \cdot \tan\alpha \tag{B.8}$$

B.4 Comparison of the approximations

On account of Formulae (B.1) and (B.8), there exists between the approximate value $t_{d,\,apr}$ and the exact value t_d the relation

$$t_{d,\,apr} = \frac{2 \cdot \tan\alpha}{(1/l_-) + (1/l_+)} = \frac{2 \cdot \sin\alpha}{\sin(\alpha - \delta) + \sin(\alpha + \delta)} \cdot t_d \tag{B.9}$$

The relative deviation Δ_{apr}, as a percentage, between the dry-film thickness t_d calculated with Formulae (B.1) and (B.4) and the approximate value $t_{d,\,apr}$ according to Formula (B.8) results with Formula (B.9):

$$\Delta_{apr} = \frac{t_{d,\,apr} - t_d}{t_d} \cdot 100 = \left(\frac{2 \cdot \sin\alpha}{\sin(\alpha - \delta) + \sin(\alpha + \delta)} - 1 \right) \cdot 100 \tag{B.10}$$

δ is limited to the range $0 \le \delta < \alpha$, and in the limit case $\delta \to \alpha$, Δ_{apr} converges against the maximum value Δ_{lim}, as a percentage, and results with Formula (B.10):

$$\Delta_{lim} = \left(\frac{2 \cdot \sin\alpha}{\sin(2 \cdot \alpha)} - 1 \right) \cdot 100 = \left(\frac{1}{\cos\alpha} - 1 \right) \cdot 100 \tag{B.11}$$

On the other hand, the following applies with Formula (B.1) for the averaged film thickness $\overline{t_d}$ according to Formula (B.5):

$$\overline{t_d} = \frac{l_- + l_+}{2} \cdot \tan\alpha = \left(\frac{1}{\sin(\alpha - \delta)} + \frac{1}{\sin(\alpha + \delta)} \right) \cdot \frac{\sin\alpha}{2} \cdot t_d \tag{B.12}$$

and the relative deviation $\overline{\Delta}$, as a percentage, between the dry-film thickness t_d calculated exactly with Formulae (B.1) and (B.4) and the averaged film thickness $\overline{t_d}$ according to Formula (B.12):

$$\overline{\Delta} = \frac{\overline{t_d} - t_d}{t_d} \cdot 100 = \left[\left(\frac{1}{\sin(\alpha - \delta)} + \frac{1}{\sin(\alpha + \delta)} \right) \cdot \frac{\sin\alpha}{2} - 1 \right] \cdot 100 \tag{B.13}$$

Table B.1 lists for the typical wedge-cut angles α = 5,7° (tan α = 0,10) and α = 14° (tan α = 0,25) and based on specified ratios l_-/l_+ of the measuring variables l_- and l_+ the following numerical values:

— δ, calculated from (l_-/l_+) and α with Formula (B.4);

— $\overline{\Delta}$, calculated from α and δ with Formula (B.13);

— Δ_{apr}, calculated from α and δ with Formula (B.10).

Table B.1 — Comparison of the approximations

l_-/l_+	α = 5,7° tan α = 0,10			α = 14° tan α = 0,25		
	δ°	$\bar{\Delta}$ %	Δ_{apr} %	δ°	$\bar{\Delta}$ %	Δ_{apr} %
1,1	0,3	0,2	<0,1	0,7	0,2	<0,1
1,2	0,5	0,8	<0,1	1,3	0,9	<0,1
1,3	0,7	1,7	<0,1	1,9	1,8	<0,1
1,4	1,0	2,9	<0,1	2,4	2,9	<0,1
1,5	1,1	4	<0,1	2,9	4	0,1
2,0	1,9	13	<0,1	4,8	13	0,3
2,5	2,4	23	<0,1	6,1	23	0,6
3,0	2,9	33	0,1	7,1	34	0,8
4,0	3,4	57	0,2	8,5	58	1,1
5,0	3,8	80	0,2	9,4	82	1,4

The data in Table B.1 shows that the approximation $t_d \approx \bar{t}_d$ may only be used for $l_-/l_+ < 1{,}5$, while the approximation $t_d \approx \Delta_{apr}$ is permissible in the entire indicated l_-/l_+ range. Also, Δ_{apr} is limited by Δ_{lim}, whereby according to Formula (B.11) the following applies:

— $\Delta_{apr} < \Delta_{lim}$ = 0,5 % for α = 5,7° (tan α = 0,10),

— $\Delta_{apr} < \Delta_{lim}$ = 3,1 % for α = 14° (tan α = 0,25).

$\bar{\Delta}$ in contrast diverges in the limit case $\delta \rightarrow \alpha$ [see Formula (B.13)].

Annex C
(informative)

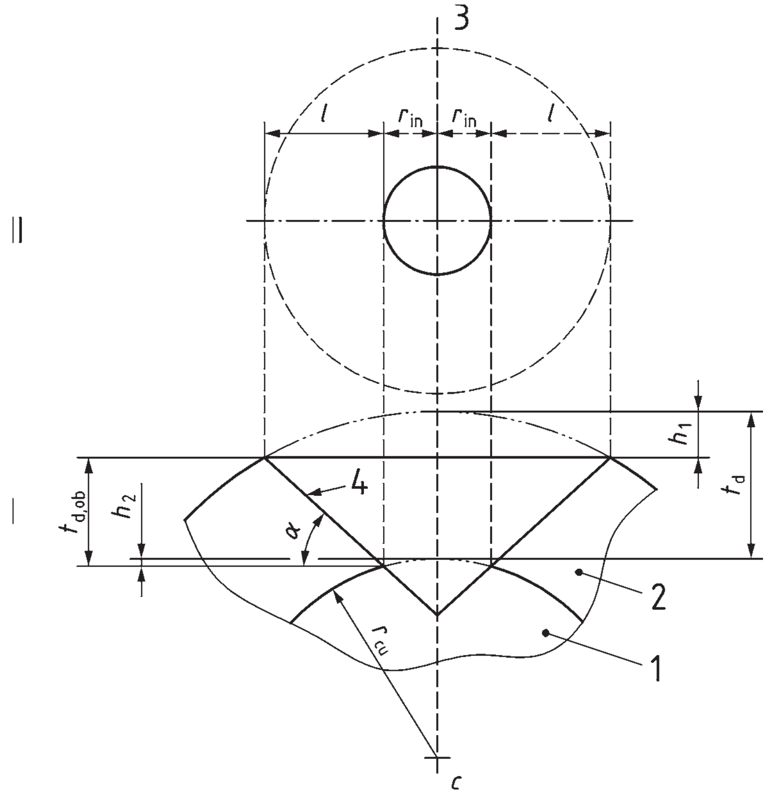
Evaluation with curved specimen

C.1 Basic principles

Figure C.1 shows a wedge cut on a convex curved specimen for drilling method B.

NOTE 1 The wedge-cut image shown in Figure C.1 II corresponds to the special case where the curvature of the specimen is only determined by one radius of curvature (“spherical geometry”). In the general case, however, two radii are necessary to describe the curvature, and the wedge-cut image then has a correspondingly different form. In the considerations below, r_{cu} is understood as the radius of the circle of curvature in the plane that cuts the specimen vertically in the area of the bore drill and progresses in the wedge-cut image according to Figure C.1 through $l - r_{in} - r_{in} - l$.

In the calculations below, it is presupposed that the specimen has a convex curvature (see Figure C.1). In the case of a concave curvature, r_{cu} shall be replaced by $-r_{cu}$ in all formulae.



Key

1	substrate	$t_{d, ob}$	observed apparent dry-film thickness ($t_{d, ob} = l \cdot \tan \alpha$)
2	coating	h_i	sagittal height (i = 1, 2)
3	drill axis	r_{in}	radius of the inner circle in the wedge-cut image
4	wedge-cut flank (bore cone)	c	centre of the circle of curvature
I	geometrical details	α	wedge-cut angle
II	wedge-cut image	r_{cu}	radius of curvature
l	wedge-cut basis		
t_d	true dry-film thickness		

Figure C.1 — Wedge cut according to method B on convex curved specimen

Figure C.1 is used to read off

$$t_{\mathrm{d}} = t_{\mathrm{d,\,ob}} + (h_1 - h_2) \tag{C.1}$$

with

$$h_1 = (r_{\mathrm{cu}} + t_{\mathrm{d}}) \cdot \left(1 - \sqrt{1 - \frac{(l + r_{\mathrm{in}})^2}{(r_{\mathrm{cu}} + t_{\mathrm{d}})^2}} \right) \tag{C.2}$$

and

$$h_2 = r_{\mathrm{cu}} \cdot \left(1 - \sqrt{1 - \frac{{r_{\mathrm{in}}}^2}{{r_{\mathrm{cu}}}^2}} \right) \tag{C.3}$$

Adding Formulae (C.1) to (C.3) yields for $t_{\mathrm{d}} \ll r_{\mathrm{cu}}$:

$$t_{\mathrm{d}} \approx t_{\mathrm{d,\,ob}} + r_{\mathrm{cu}} \cdot \left(\sqrt{1 - \frac{{r_{\mathrm{in}}}^2}{{r_{\mathrm{cu}}}^2}} - \sqrt{1 - \frac{(l + r_{\mathrm{in}})^2}{{r_{\mathrm{cu}}}^2}} \right) \tag{C.4}$$

Formula (C.4) shows that the true dry-film thickness t_{d} with convex curvature, as also revealed from Figure C.1, is always greater than the apparent dry-film thickness $t_{\mathrm{d,\,ob}}$. In the case of concave curvature, on the other hand, $t_{\mathrm{d}} < t_{\mathrm{d,\,ob}}$ applies, as then r_{cu} shall be replaced by $-r_{\mathrm{cu}}$.

NOTE 2 According to Formula (C.4), the apparent film thickness $t_{\mathrm{d,\,ob}}$ depends on the radius r_{in} and hence, also on the drilling depth $h = r_{\mathrm{in}} \cdot \tan \alpha + h_2$ (see Figure C.1) into the substrate.

For l, $r_{\mathrm{in}} \ll r_{\mathrm{cu}}$, the root terms in Formula (C.4) can be approximated linearly [$\sqrt{1-\alpha} \approx 1 - \frac{\alpha}{2}$ for $\alpha \ll 1$], and after transformation the following is obtained:

$$t_{\mathrm{d}} \approx t_{\mathrm{d,\,ob}} + \frac{l^2 + 2 \cdot l \cdot r_{\mathrm{in}}}{2 \cdot r_{\mathrm{cu}}} \tag{C.5}$$

Following from this with $l = t_{\mathrm{d,\,ob}}/\tan \alpha$:

$$t_{\mathrm{d}} \approx t_{\mathrm{d,\,ob}} \left[1 + \frac{t_{\mathrm{d,\,ob}}}{2 \cdot r_{\mathrm{cu}} \cdot \tan^2 \alpha} \cdot 1 + \frac{2 \cdot r_{\mathrm{in}}}{l} \right] \tag{C.6}$$

The true film thickness t_{d} can be calculated with Formula (C.6), if

— method B is used,

— the drill axis is aligned radially (i.e. to the centre of the circle of curvature),

— in addition to the wedge-cut basis, l, the circle diameter $2 \cdot r_{\mathrm{in}}$ (see Figure C.1) is known,

— the radius of curvature r_{cu} is known (but see also C.3), and

— the boundary conditions l, t_{d}, $r_{\mathrm{in}} \ll r_{\mathrm{cu}}$ are fulfilled.

C.2 Evaluation if radius of curvature is known

For simplification of Formula (C.6) the auxiliary variable

$$L = l + 2 \cdot r_{\text{in}} \tag{C.7}$$

is introduced.

NOTE If the scale measuring range of the microscope is sufficient, L can also be measured directly.

On account of $2 \cdot r_{\text{in}} = L - l$ according to Formula (C.7) and $t_{\text{d, ob}} = l \cdot \tan \alpha$ the following is obtained with Formula (C.6):

$$t_{\text{d}} \approx l \cdot \left[1 + \frac{l}{2 \cdot r_{\text{cu}} \cdot \tan \alpha} \cdot \left(1 + \frac{L - l}{l}\right) \right] \cdot \tan \alpha \tag{C.8}$$

and the true dry-film thickness t_{d} can be calculated if the radius of curvature r_{cu} is known with

$$t_{\text{d}} \approx l \cdot \tan \alpha + \frac{l \cdot L}{2 \cdot r_{\text{cu}}} \tag{C.9}$$

C.3 Evaluation if radius of curvature is not known

If two wedge-cut bores are performed at points of equal curvature with different drilling depths into the substrate and the associated l and L values (or r_{in} values) are measured, the radius of curvature r_{cu} can be calculated.

For the values l_i and L_i measured at the wedge-cut bore i the following applies with Formula (C.9) ($i = 1, 2$)

$$l \approx l_i \cdot \tan \alpha + \frac{l_i \cdot L_i}{2 \cdot r_{\text{cu}}} \tag{C.10}$$

or after equating

$$l_1 \cdot \tan \alpha + \frac{l_1 \cdot L_1}{2 \cdot r_{\text{cu}}} \approx l_2 \cdot \tan \alpha + \frac{l_2 \cdot L_2}{2 \cdot r_{\text{cu}}} \tag{C.11}$$

from which r_{cu} can be separated:

$$r_{\text{cu}} \approx \frac{(l_1 \cdot L_1 - l_2 \cdot L_2)}{2 \cdot (l_2 - l_1) \cdot \tan \alpha} \tag{C.12}$$

After inserting Formula (C.12) in Formula (C.10) it follows in both cases ($i = 1, 2$)

$$t_{\text{d}} \approx \frac{l_1 \cdot l_2 \cdot (L_1 - L_2)}{l_1 \cdot L_1 - l_2 \cdot L_2} \cdot \tan \alpha \tag{C.13}$$

With Formula (C.13), the true dry-film thickness t_{d} can also be calculated if the radius of curvature is unknown.

C.4 Limiting condition for the standard evaluation

Formula (C.6) can be used to calculate the relative deviation $\Delta_{t,\,rel} = (t_d - t_{d,\,ob}) / t_{d,\,ob}$ between the true dry-film thickness t_d and the apparent film thickness $t_{d,\,ob}$

$$\Delta_{t,\,d} \approx \frac{t_{d,\,ob}}{2 \cdot r_{cu} \cdot \tan^2\alpha} \cdot \left(1 + 2 \cdot \frac{r_{in}}{l}\right) \tag{C.14}$$

or resolved for r_{cu}

$$r_{cu} \approx \frac{t_{d,\,ob}}{2 \cdot \Delta_{t,\,d} \cdot \tan^2\alpha} \cdot \left(1 + 2 \cdot \frac{r_{in}}{l}\right) \tag{C.15}$$

Based on Formula (C.15), an estimation of the minimum radius of curvature $r_{cu,\,min}$ can be derived, above which the approximation $t_{d,\,ob} \approx t_d$ is sufficient within a specified maximum deviation Δ_{max}. In order to gain a practical and reliable estimation, the following simplifications are made.

a) As for the estimation of $r_{cu,\,min}$, only relative deviations between t_d and $t_{d,\,ob}$ of maximum $\Delta_{t,\,d} \approx 20\ \%$ are assumed, $t_{d,\,ob}$ is replaced by t_d here.

b) As r_{cu} according to Formula (C.15) via r_{in} also depends on the variable drilling depth $h = r_{in} \cdot \tan\alpha + h_2$; see Figure C.1) into the substrate, $(1 + 2 \cdot r_{in} / l) = 10$ is set here. This corresponds to $h \approx 5 \cdot t_d$, as in the case of minor curvature, i.e. $h_2 \ll (r_{in} \cdot \tan\alpha)$, it applies $r_{in}/l \approx h_{in} / t_d$.

c) Standard units are used.

This gives for the minimal radius of curvature $r_{cu,\,min}$:

$$r_{cu,\,min} \approx \frac{500 \cdot t_d}{\Delta_{max} \cdot \tan^2\alpha} \tag{C.16}$$

NOTE 1 Formula (C.16) states: If the radius of curvature r_{cu} is greater than the limit radius $r_{cu,\,min}$, the curvature effect can be neglected within an accuracy defined by Δ_{max} and the dry-film thickness can be calculated according to Formula (1) (i.e. t_d approximately $t_{d,\,ob} = l \cdot \tan\alpha$).

NOTE 2 Formula (C.16) is generally valid and not limited to method B.

NOTE 3 As $r_{cu,\,min}$ according to Formula (C.16) is proportional to (1 / tan2 α), it can be favourable to select as large a wedge-cut angle as possible.

Table C.1 lists $r_{cu,\,min}$ values that were calculated with Formula (C.16), in relation to t_d, Δ_{max} and α, tan α. Table C.1 also contains the values Δ_r for the relative dry-film thickness resolution relating to t_d and caused by the scale division (see Table 1). For $\Delta_{max} < \Delta_r / 2$, the $r_{cu,\,min}$ values are in brackets, as they make little sense.

Table C.1 — $r_{cu,\ min}$ in relation to t_d, Δ_{max} and α, tan α

	α = 5,7° tan α = 0,10				α = 14° tan α = 0,25			
t_d µm	20	50	100	200	50	100	200	500
Δ_r %	10	4	2	1	10	5	3	1
Δ_{max} %	$r$cu, min 10^6 µm							
2	(0,50)	1,25	2,51	5,02	(0,20)	(0,40)	0,80	2,01
5	0,20	0,50	1,00	2,01	0,08	0,16	0,32	0,80
10	0,10	0.25	0,50	1,00	0,04	0,08	0,16	0,40
20	0,05	0,13	0,25	0,50	0,02	0,04	0,08	0,20

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