



**International
Standard**

ISO 19606

**Fine ceramics (advanced ceramics,
advanced technical ceramics) —
Test method for surface roughness
of fine ceramic films by atomic force
microscopy**

*Céramiques techniques — Méthode d'essai pour la rugosité de
surface des films céramique fins par microscopie à force atomique*

**Second edition
2024-11**

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Published in Switzerland

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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 document 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).

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

This document was prepared by Technical Committee ISO/TC 206, *Fine ceramics*.

This second edition cancels and replaces the first edition (ISO 19606:2017), which has been technically revised.

The main changes are as follows:

- in [Clause 3](#), ISO 4287 and ISO 4288 have been replaced with ISO 21920-1-3;
- revision of [6.2](#) and [Clause 3](#);
- symbols have been revised throughout by moving text to subscript;
- [Annex A](#) changed from normative to informative.

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

Introduction

Surface roughness measurements of fine ceramic thin films at the nanometre scale by atomic force microscopy is widely applied to quality control and assurance in industries.

One frequently occurring issue in roughness measurements by atomic force microscopy resulting from its scale dependency is the deviation of roughness due to wear of the probe tip or the deviation in the curvature of commercially available probe tips. This makes it difficult to obtain a reliable and reproducible result of the roughness measurement. Therefore, it is highly desirable to standardize a method to evaluate probe tip diameter or curvature radius.

This document covers the evaluation of probe-tip diameter and provides a method to judge the adequateness of a probe tip for use in day-to-day roughness measurements of fine ceramic thin films with a certain arithmetical mean roughness in the range needing the use of atomic force microscopy in production lines or quality assurance processes.

It should be noted that because surface roughness is a scale-dependent metrology parameter, it is unavoidable that the probe-tip evaluation process contains some contradictory procedures, namely the adequateness of the probe tip for a roughness measurement depends on unmeasurable true roughness in a scale of interest.

In this document, the parameters based on roughness profiles are used. The roughness profile is obtained by using a low-pass filter according to ISO 16610-21. The process to obtain the sampling length, which is identical to cut-off wavelength, is given in ISO 21920-2. Some different sampling lengths to process a primary profile can be applied to obtain appropriate values of arithmetic mean deviation of a roughness profile, if necessary.

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Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for surface roughness of fine ceramic films by atomic force microscopy

1 Scope

This document specifies a method to evaluate the adequateness of a probe tip for fine-ceramic thin-film surface roughness measurements by atomic force microscopy. This method applies to surfaces with an arithmetical mean roughness, R_a , in the range of about 1 nm to 30 nm and a mean width of roughness profile elements, R_{sm} , in the range of about 0,04 μm to 2,5 μm .

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 11039, *Surface chemical analysis — Scanning-probe microscopy — Measurement of drift rate*

ISO 11952, *Surface chemical analysis — Scanning-probe microscopy — Determination of geometric quantities using SPM: Calibration of measuring systems*

ISO 18115-2, *Surface chemical analysis — Vocabulary — Part 2: Terms used in scanning-probe microscopy*

ISO 21920-1, *Geometrical product specifications (GPS) — Surface texture: Profile — Part 1: Indication of surface texture*

ISO 21920-2, *Geometrical product specifications (GPS) — Surface texture: Profile — Part 2: Terms, definitions and surface texture parameters*

ISO 21920-3, *Geometrical product specifications (GPS) — Surface texture: Profile — Part 3: Specification operators*

ISO 25178-2, *Geometrical product specifications (GPS) — Surface texture: Areal — Part 2: Terms, definitions and surface texture parameters*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 21920-1, ISO 21920-2, ISO 21920-3, ISO 18115-2, ISO 11039, ISO 11952 and ISO 25178-2 and the following apply.

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

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

3.1 evaluation length

$l_e(X)$, $l_e(Y)$

length of surface profile in the X or Y direction

3.2

probe-tip diameter evaluation standard plate

plate on which needle-shaped spikes are formed

Note 1 to entry: The plate is used to evaluate the *probe-tip diameter* (3.3).

3.3

probe-tip diameter

D

diameter of a probe tip at a distance of 10 nm from the tip end

4 Test environment

Testing shall be carried out only where temperature change, sound noise and mechanical vibration of the floor or walls are sufficiently low to perform the measurements. The following installation environment is recommended:

- a) temperature: 18 °C to 25 °C;
- b) humidity: 70 % or less;
- c) noise level: 60 dB or less;
- d) mechanical vibration of the floor or the wall: $1 \times 10^{-3} \text{ m/s}^2$ (<100 Hz) or less.

5 Roughness measurement specimens

Specimens for roughness measurements are ceramic thin films on a substrate. Any kinds of substrate material can be used, such as metal, glass, polymer, etc. The specimen shall be no larger than the specimen stage of the instrument being used.

6 Test apparatus

6.1 Atomic force microscopy system

The atomic force microscopy (AFM) system consists of a cantilever, the detecting system for the cantilever deflection, and the sample stage with XYZ motion to displace the sample, including a piezoelectric positioning system. The AFM system should be put on an anti-vibration table inside an acoustic enclosure in order to fulfil the requirements on noise level and mechanical vibration given in [Clause 4](#).

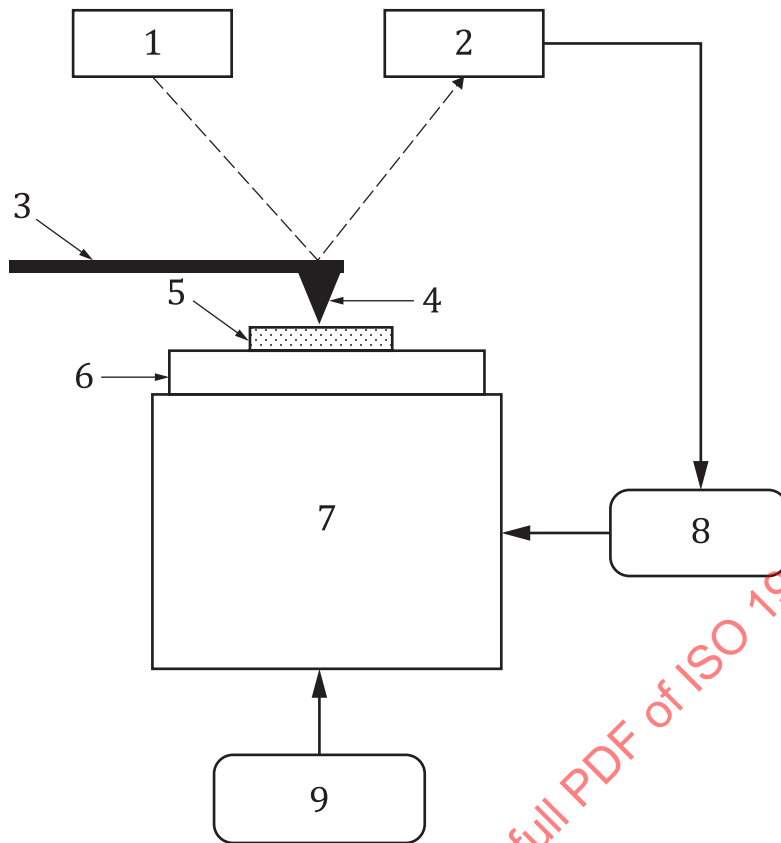
6.2 Cantilever

The cantilever shall be exclusively dedicated for a dynamic mode and commercially available. The resonant frequency should be higher than 100 kHz.

6.3 Scanner

The scanner shall be capable of scanning the cantilever or specimen stage by shifting the XYZ position. The scanning area should be larger than $10 \mu\text{m} \times 10 \mu\text{m}$ in the XY plane.

[Figure 1](#) shows an example of a measurement system having a specimen stage scan mechanism. Position in the Z direction is controlled using a Z-position control circuit that keeps a constant separation between the probe and the specimen surface. For this purpose, a light beam from a laser diode illuminates the cantilever and the reflected beam position is monitored by a light detector. The surface profile is measured by scanning the specimen stage in the XY plane.



Key

- | | | | |
|---|----------------|---|----------------------------|
| 1 | laser diode | 6 | specimen stage |
| 2 | light detector | 7 | X, Y and Z scanner |
| 3 | cantilever | 8 | Z-position control circuit |
| 4 | probe tip | 9 | X-Y scan circuit |
| 5 | specimen | | |

Figure 1 — Schematic of an AFM system

6.4 Specimen stage

The specimen stage shall be capable of supporting a specimen horizontally. The test area of the specimen should be in the centre of the specimen stage. Scanning should be performed near the centre of the X, Y and Z axes of the scanner used.

7 Test apparatus calibration

This document only describes a method to evaluate the adequateness of a probe tip for fine-ceramic thin-film surface roughness measurements by atomic force microscopy. If the apparatus needs to be calibrated, refer to standards describing calibration criteria and methods for a scanning probe microscope; see ISO 21920-1, ISO 21920-2, ISO 11039, ISO 11775, and ISO 11952.

8 Probe-tip diameter evaluation standard plate

A standard for probe-tip diameter evaluation is a plate on which a number of needle-shaped spikes, arranged in a square matrix, are formed. The needle-shaped spikes are typically as follows:

- tip curvature radius: 10 nm;

- tip aperture angle: 20° or 50°;
- tip height: 300 nm to 600 nm;
- distance between any two nearest neighbour tips: 2,12 µm;
- plate size: 5 mm × 5 mm.

9 Calibration of X-Y and Z scan axes

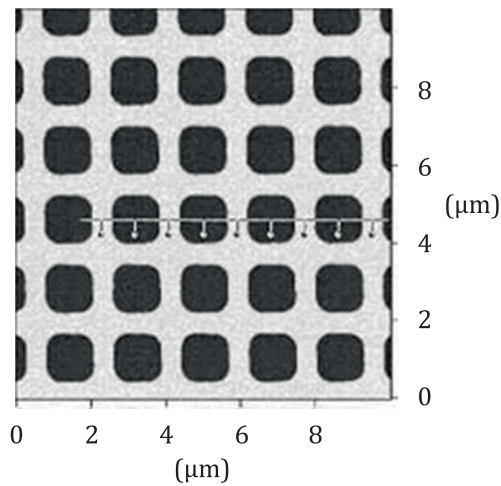
The calibration of the X-Y scanner and Z scanner should be carried out by measuring the X, Y and Z profile of a certified calibration standard. The standard should have a grating with a certain pitch and a step with a certain height.

The standard sample is a specimen with calibrated height and pitch, which are certified and traceable with uncertainty data attached. It is recommended that the grating pitch is less than 2 µm and that the step height is less than 20 nm.

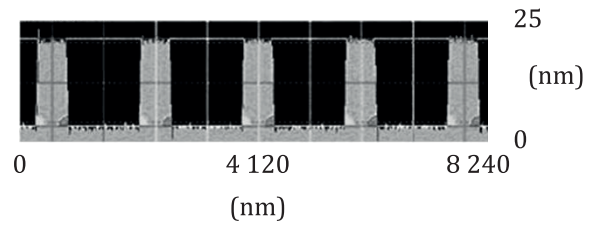
The calibration standard should be stored in a clean and dry box and be handled with care.

The calibration shall be carried out in the following sequence using the dynamic mode.

- a) Mount the calibration standard in such a way that the grating is oriented to the X-Y axes of the scanner and that its plane lies nearly parallel to the X-Y plane of the scanner.
- b) Set the number of picture elements at 512 × 512 or 256 × 256.
- c) Scan an area of about 10 µm square of the calibration standard and store the surface profile data. An example is shown in [Figure 2 a\)](#).
- d) From the surface profile data, draw a surface profile along the X direction at a selected Y position where the surface profile contains several steps on the calibration standard and level off the one-dimensional profile along the X direction. An example is shown in [Figure 2 b\)](#).
- e) Measure profile peak height at the centre of top and bottom sections of the profile. Calculate mean height for at least five successive profile elements in the profile along the X direction.
- f) Measure a pitch along the X direction by measuring the distance between the mid-points of two successive rising or falling parts of the profile.
- g) From the surface profile data, draw a surface profile along the Y direction at a selected X position where the surface profile contains several steps and level off the one-dimensional profile along the Y direction.
- h) Measure profile peak heights at the centre of top and bottom sections of the profile. Calculate mean height for at least five successive profile elements in the profile along the Y direction.
- i) Measure a pitch along the Y direction by measuring the distance between the mid-points of two successive rising or falling parts of the profile.
- j) If an X- or Y-pitch measured is out of the range of uncertainty needed for roughness measurements, correct X or Y values by obtaining an X- or Y-axis calibration factor.
- k) If the mean height obtained is out of the range of uncertainty needed for roughness measurements, correct Z values by obtaining a Z-axis calibration factor.



a) Surface profile



b) Surface profile along the X direction

Figure 2 — Examples of surface profile data for the calibration of the X-Y scanner and Z scanner

10 Probe-tip error evaluation

10.1 Outline of probe-tip error evaluation

The error for roughness measurements using a probe tip with a certain probe-tip diameter shall be evaluated by using a probe-tip error evaluation template, providing the error from the relationship between the probe-tip diameter, preliminary R_a and preliminary R_{sm} . If a probe tip is judged to be unsuitable for a roughness measurement with a certain error for a specimen to be measured, it should be rejected and replaced with a new one.

Probe-tip evaluation shall be carried out using the probe-tip evaluation sequence shown in [Figure 3](#).

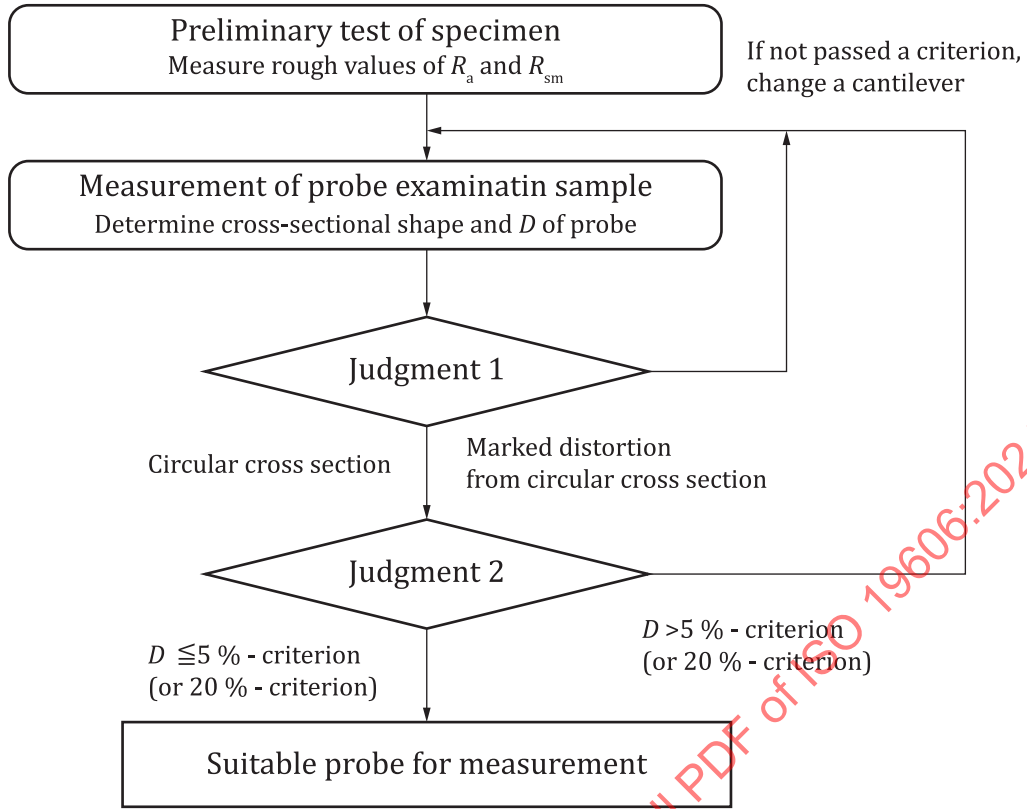


Figure 3 — Probe-tip evaluation sequence

10.2 Measurements of preliminary R_a and R_{sm}

Preliminary roughness measurements shall be carried out to obtain preliminary, the arithmetic mean height parameter, R_a , and the mean profile elements spacing parameter, R_{sm} , the values to be used in the probe-tip judgement procedure.

- Place the specimen to be measured on the specimen stage without any surface treatment or without using any adhesive.
- Choose arbitrarily a measuring position on the specimen.
- Set the number of picture elements at 256 pixels or 512 pixels in the X direction and the scanning speed within 0,5 Hz to 1 Hz.
- Scan a 2 μm line in the X direction at a fixed Y position using the dynamic mode. Again, scan a 10 μm line in the X direction at the same Y position. Apply an appropriate cut-off length.
- Select one of the two surface profiles along the X direction, such that the number of profile elements in the evaluation length $l_e(X)$ is between 20 and 50.
- Calculate preliminary R_a and R_{sm} values from the selected surface profile using [Formulae \(1\)](#) and [\(2\)](#), respectively.

$$R_a = \frac{1}{l_e} \int_0^{l_e} |Z(x)| dx \quad (1)$$

$$R_{sm} = \frac{1}{n_{pe}} \sum_{i=1}^{n_{pe}} X_{s,i} \quad (2)$$

where

l_e is the evaluation length;

$Z(x)$ is the absolute ordinate at the position x within the sample length;

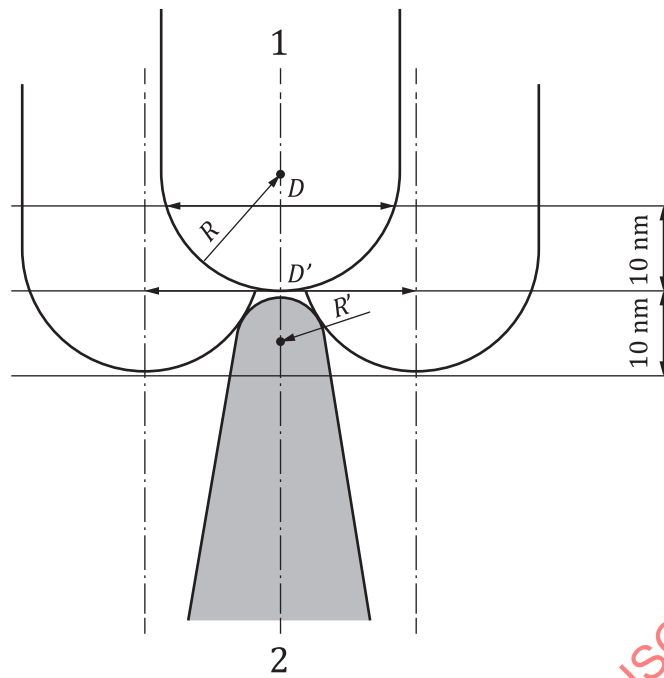
n_{pe} is the number of the profile elements;

X_s is the profile element spacing.

10.3 Evaluation of probe-tip diameter

The evaluation of probe-tip diameter should be carried out using the following sequence. A schematic drawing of probe-tip diameter determination is shown in [Figure 4](#).

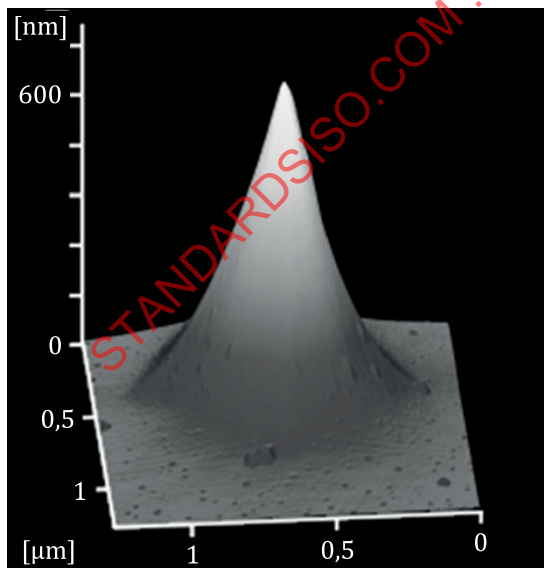
- a) Measure a part of the probe-tip diameter evaluation standard plate by scanning a $2\ \mu\text{m} \times 2\ \mu\text{m}$ to $3\ \mu\text{m} \times 3\ \mu\text{m}$ squared area with the number of picture elements ranging from $128\ \text{pixels} \times 128\ \text{pixels}$ to $32\ \text{pixels} \times 32\ \text{pixels}$ to identify a needle-shaped spike on the standard plate to be used in a probe-tip diameter measurement.
- b) Confirm one of needle-shaped spikes on the surface is profiled.
- c) Adjust the scanning area so that the centre of the needle-shaped spike lies in the centre of the measured area.
- d) Measure again the area under the following conditions: the scan area of 1×1 to $1,28\ \mu\text{m} \times 1,28\ \mu\text{m}$ squared, picture elements of $512\ \text{pixels} \times 512\ \text{pixels}$ and a scan speed of 0,5 Hz. Apply an appropriate cut-off length (typically 300 nm to 700 nm).
- e) Draw the cross section of the needle-shaped spike profiled at 10 nm below its top in the Z direction. An example of such a cross section is shown in [Figure 5 b](#)). If the shape is markedly distorted from circular, the probe tip should be rejected and replaced with a new one. The tip-diameter evaluation should be repeated for the new probe tip (judgment 1). It is recommended to draw a bird's-eye view of the profile as shown in [Figure 5 a](#)).
- f) If the ratio between the smallest dimension and largest dimension of the cross section drawn in e) is less than a factor of 0,8 then measure another tip. If not, then calculate the probe-tip diameter as described in [Annex A](#). For the purposes of the calculation of D , assume that the diameter of the cross section drawn in e), d , is the average of the smallest and largest dimensions. Regard the calculated diameter as the probe-tip diameter, D . The determination of D is described in [Annex A](#).



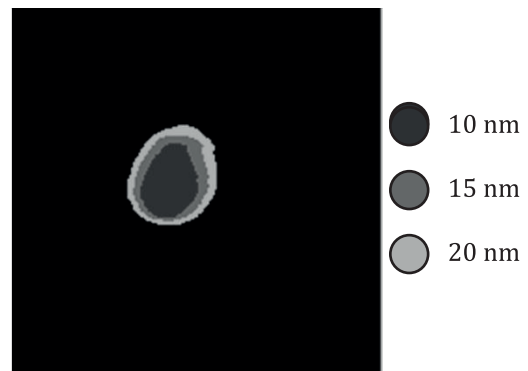
Key

- 1 probe tip
- 2 one of the needle-shaped spikes on the probe-tip evaluation standard plate
- R probe-tip curvature radius
- R' curvature radius of a needle-shaped spike
- D probe-tip diameter
- D' characterized probe-tip diameter, the distance between the probe centre at the depth of 10 nm beneath the top of the needle-shaped spike on the probe-tip evaluation standard plate

Figure 4 — Schematic drawing of fundamentals of probe-tip diameter determination



a) Bird's-eye view of measured surface profile



b) Cross section

Figure 5 — Example of measured data of one of the needle-shaped spikes on the probe-tip diameter evaluation standard plate, diameter, D' : 27,3 nm

10.4 Evaluation of error in roughness measurements

Judge if the D obtained in 10.3 is suitable or not for roughness measurement of a specimen to be measured by applying one of the error evaluation templates given in Figures 6 to 9 (judgment 2).

A 5 %-criterion and a 20 %-criterion are defined, which enable roughness measurements with an error less than 5 % and 20 %, respectively. Fundamental assumptions of the criteria are described in Annex B.

Figure 10 shows how to use the error evaluation templates given in Figures 6 to 9 for the probe-tip error evaluation. For a given rough value of R_{sm} , if D is placed above the solid line in the D - R_{sm} map, for example $D = D1$, the probe tip is not suitable for roughness measurements of a specimen to be examined because measurement error due to tip diameter exceeds 20 %. If D is placed below the solid line, for example $D = D2$, the probe tip enables roughness measurements with an error <20 %. If D is placed below the dotted line, for example $D = D3$, the probe tip enables roughness measurements with an error <5 %. Templates given in Figures 6 to 9 show 5 %-criterion and 20 %-criterion for specimens with $R_a = 1$ nm, 3 nm, 10 nm and 30 nm, respectively. Apply one of the criteria depending on the required accuracy of roughness measurements.

If the probe tip is not applicable for roughness measurement of a specimen with a certain evaluation error, replace the probe tip and evaluate the probe-tip error again by using the procedure described in 10.3.

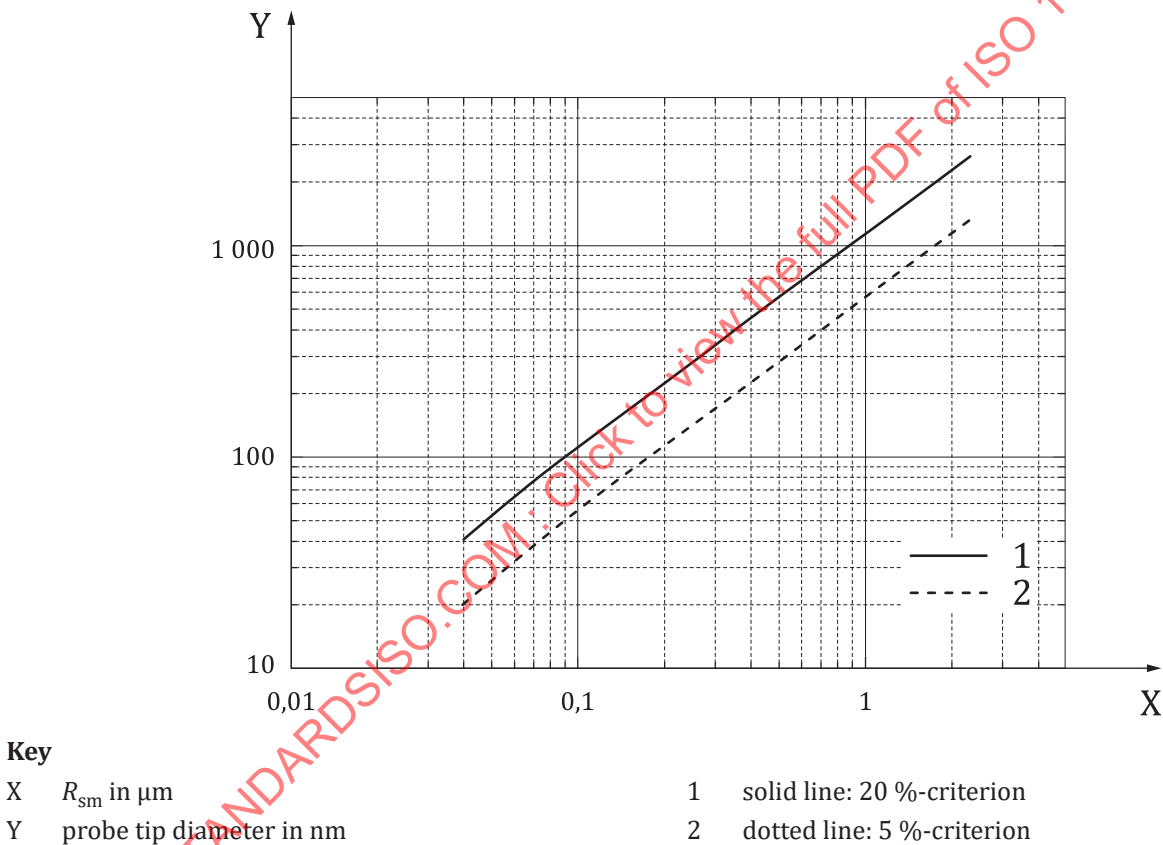
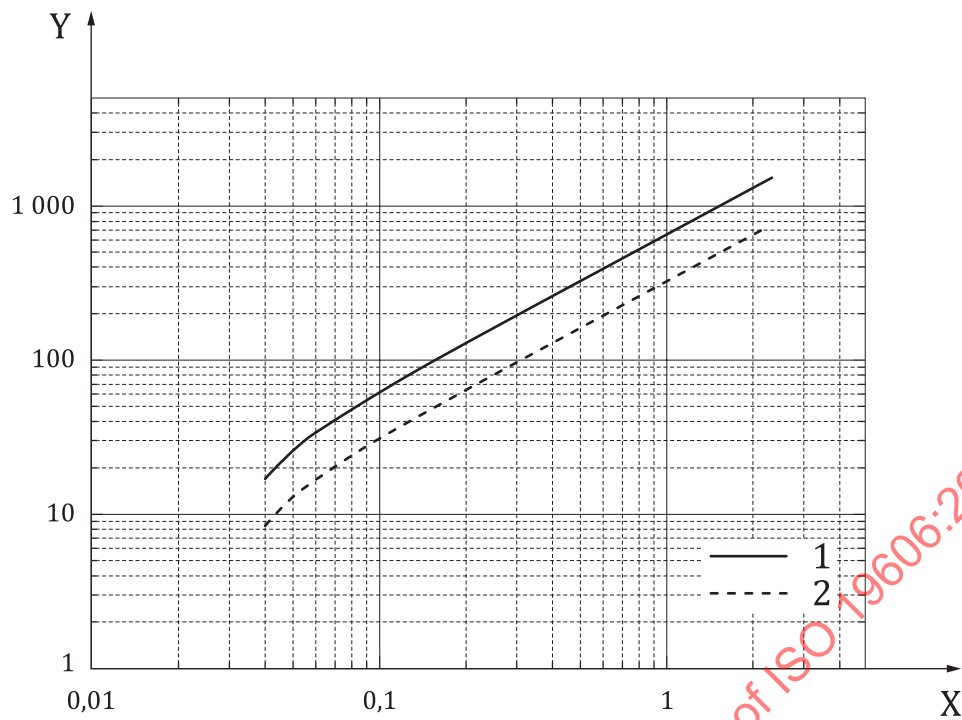


Figure 6 — D - R_{sm} map for probe-tip error evaluation to measure roughness of a specimen with preliminary R_a of 1 nm



Key

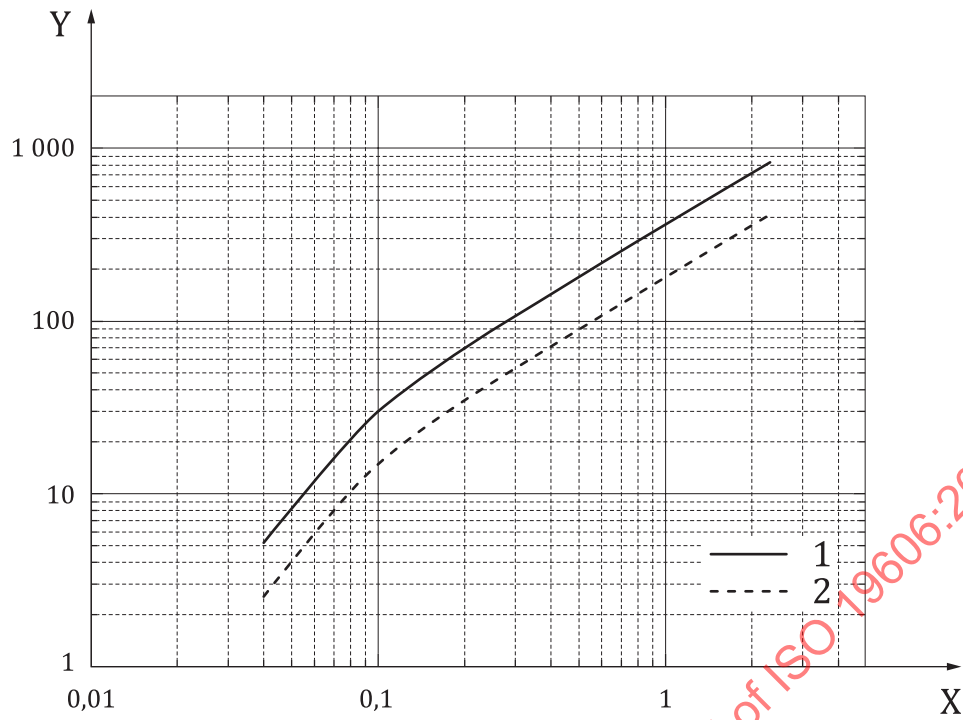
X R_{sm} in μm

Y probe tip diameter in nm

1 solid line: 20 %-criterion

2 dotted line: 5 %-criterion

Figure 7 — D - R_{sm} map for probe-tip error evaluation to measure roughness of a specimen with preliminary R_a of 3 nm



Key

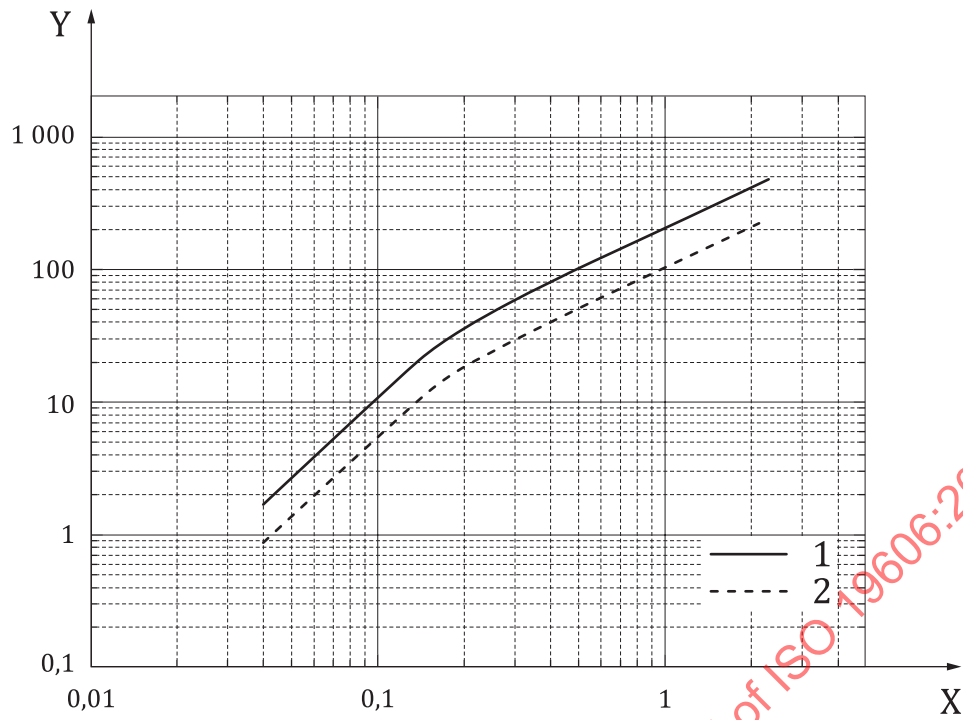
X R_{sm} in μm

Y probe tip diameter in nm

1 solid line: 20 %-criterion

2 dotted line: 5 %-criterion

Figure 8 — D - R_{sm} map for probe-tip error evaluation to measure roughness of a specimen with preliminary R_a of 10 nm



Key

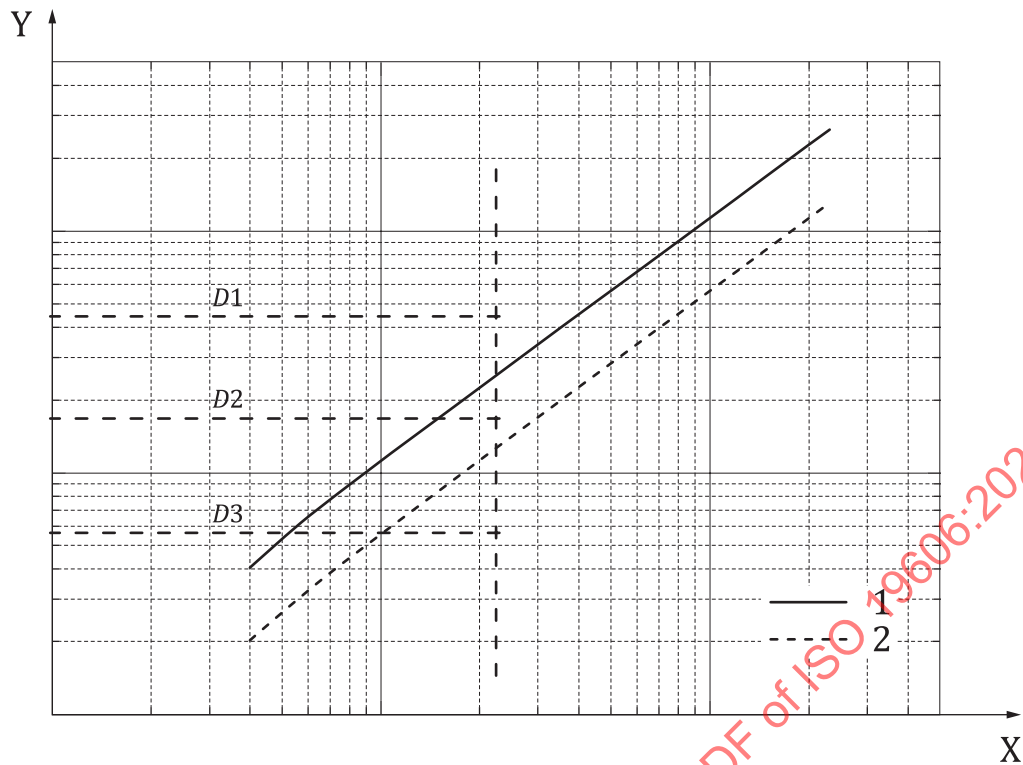
X R_{sm} in μm

Y probe tip diameter in nm

1 solid line: 20 %-criterion

2 dotted line: 5 %-criterion

Figure 9 — D - R_{sm} map for probe-tip error evaluation to measure roughness of a specimen with preliminary R_a of 30 nm



Key

X	R_{sm}	1	solid line: 20 %-criterion
Y	probe tip diameter	2	dotted line: 5 %-criterion

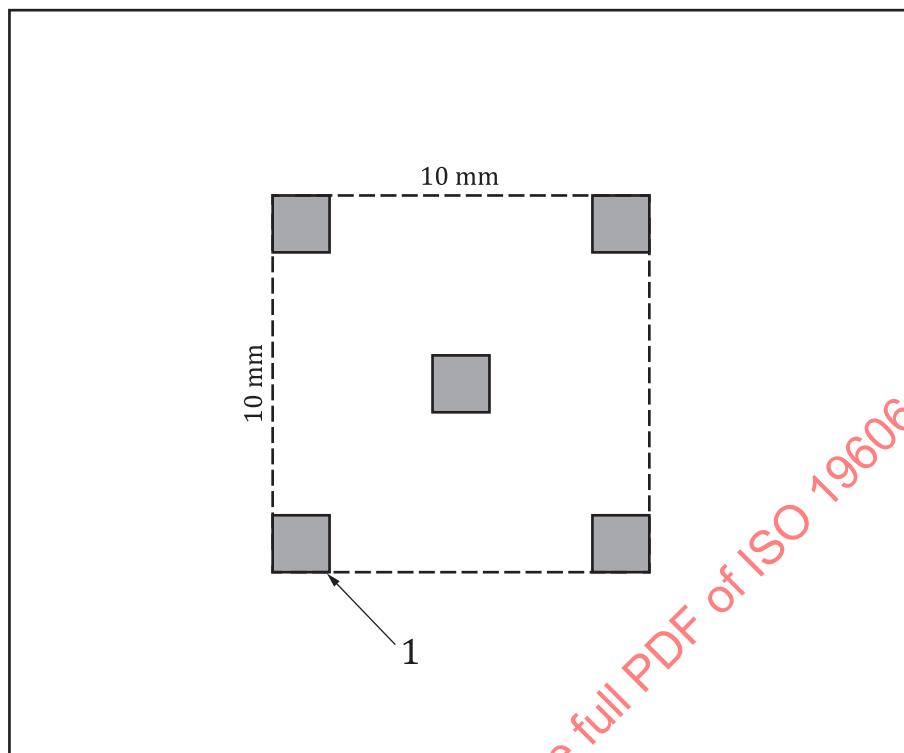
Figure 10 — D - R_{sm} map describing how to apply the templates of Figures 6 to 9 for probe-tip evaluation

11 Roughness measurements of specimen

Roughness measurements shall be carried out using an evaluated probe tip and under the measurement conditions given in [Clause 4](#). The roughness measurement sequence shall be as follows.

- Mount the specimen to be measured as described in [Clause 5](#).
- Choose a number of measuring points on the specimen. For example, four corners and the centre of a 10 mm square in the middle area of the specimen as shown in [Figure 11](#).
- Select the number of picture elements from 256 pixels to 512 pixels in the X direction and from 10 pixels to 512 pixels in the Y direction. Evaluation lengths $l_e(X)$ and $l_e(Y)$ are chosen so as to contain 20 periods to 50 periods of the profile elements. Apply an appropriate cut-off length to suppress a long-wave component. [Table 1](#) shows the recommended evaluation lengths for each preliminary R_{sm} value of the specimen. Pixels in the Y direction can be 10 pixels if the average roughness of a line profile is measured.
- Scan the surface of the specimen at the given conditions.
- Repeat the evaluation of the probe-tip diameter, D , when, during a series of roughness measurements, a change in image is observed that can be due to wear of the probe tip. If the change in the probe-tip diameter is confirmed by the probe-tip diameter evaluation, the roughness measurement conditions should be reconsidered.
- Calculate R_a or S_a of the specimen using numerical data of the surface profile after compensating for any specimen tilt from the horizontal.

- g) Obtain R_z or S_z of the specimen using numerical data of the roughness profile after compensating for any specimen tilt from the horizontal by referring to ISO 25178-2 and ISO 25178-3 (R_z is maximum height of the profile and S_z is maximum height of the surface).



Key

- 1 measuring points

Figure 11 — Measuring positions on the specimen: four corners and the centre of a 10 mm square in the middle area

Table 1 — Recommended evaluation length for roughness measurements

Preliminary R_{sm} μm	Recommended evaluation length l_e (μm)
$0,04 < R_{sm} < 0,10$	2
$0,10 \leq R_{sm} < 0,20$	5
$0,20 \leq R_{sm} < 0,40$	10
$0,40 \leq R_{sm} < 1,0$	20
$1,0 \leq R_{sm} < 2,5$	50

12 Test report

The test report shall contain the following items as a minimum:

- type, material and shape of the test specimens;
- date of the test, name of person conducting the test, and name and address of the testing establishment;
- a reference to this document, i.e. ISO 19606:2024;
- manufacturer, model number and specification of the measurement system;
- type and detailed shapes of probe-tip diameter evaluation standard;

- f) manufacturer and number of standard used to calibrate X , Y and Z axes of the instrument;
- g) temperature and humidity in the measurement room;
- h) test conditions used (material of the probe, model number of cantilever, resonant frequency, vibration frequency, Q value, scanning area, scanning speed, number of picture elements, and kind and shape of specimen holder if used);
- i) probe-tip evaluation data (bird's-eye profile data, cross-section data, probe-tip diameter evaluated);
- j) test result data (images of roughness measurements and values of R_a or S_a , R_z or S_z , etc.);
- k) any deviations from the procedure;
- l) any remarks about the testing circumstances;
- m) any unusual features observed.

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Annex A (informative)

Determination of D from D'

A.1 Conditions needed for probe-tip diameter evaluation standard plate

The values of tip curvature radius and tip aperture angle should be obtainable from the supplier.

A.2 Fundamental assumptions

Probe-tip end is spherical with a curvature radius, R .

The diameter of the needle-shaped spikes on a probe-tip diameter evaluation standard plate R' ranges from 5 nm to 10 nm.

The aperture angle of the needle-shaped spikes on a probe-tip diameter evaluation standard plate ranges from 20° to 50°.

A.3 Procedures

A probe-tip diameter D is calculated as a function of R' and D' .

Using the given values of the curvature radius, R' , and θ , the value of D' , i.e. the diameter of the cross section of the spike drawn in 10.3 e), calculate the curvature radius of the probe tip. The formula used for this calculation depends on the values of the angular aperture of the needle-shaped spike and measured D' . There are two cases: $D' \geq D'_{\text{crit}}$ and $D' < D'_{\text{crit}}$, where D'_{crit} is the diameter measured for the radius of the probe tip when, for the conditions shown in Figure 4, contact between it and the needle-shaped spike occurs at the transition point between the curved tip of the spike and its conical base for a certain angular aperture. D'_{crit} is given by Formula (A.1):

$$D'_{\text{crit}} = 2R = 2 \frac{10}{1 - \sin(\theta/2)} \cos(\theta/2) \quad (\text{A.1})$$

For aperture curvature to be considered in the measurements, D'_{crit} is given for the sake of convenience in Table A.1.

Table A.1 — D'_{crit} for various aperture angles

Aperture angle (°)	20	30	40	50
D'_{crit} (nm)	47,6	52,2	47,2	62,8

For $D' < D'_{\text{crit}}$, use [Formula \(A.2\)](#):

$$D = 2R = 2 \left(\frac{D'^2}{40} + 10 - 2R' \right) \quad (\text{A.2})$$

For $D' \geq D'_{\text{crit}}$, use [Formula \(A.3\)](#):

$$D = 2R = \frac{\frac{D'}{2} - \frac{R'}{\cos(\theta/2)} + (R' - 10)\tan(\theta/2)}{[1 - \sin(\theta/2)]\tan(\theta/2) + \cos(\theta/2)} \quad (\text{A.3})$$

where θ is the aperture angle of the needle-shaped spike.

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Annex B (informative)

Method to determine criteria for probe-tip error

B.1 Fundamental assumptions

The desirable D to measure surface roughness with a certain accuracy is calculated using a model shown in [Figure B.1](#) assuming as follows.

- a) Surface profile of the specimen $f(x)$ is given by:

$$f(x) = \frac{\pi R_a}{2} \cos\left(\frac{2\pi}{R_{sm}} x\right)$$

(B.1)

because $R_a = \frac{R_z}{\pi}$

This R_a value agrees well with real specimen surfaces compared with that of a triangular- or rectangular-shaped surface because the real surface can be approximated by the sum of cosine curves.

- b) The probe-tip has a spherical shape with radius R .
- c) The probe-tip shall reach the base of the valleys of the surface. Therefore, the maximum value of tip radius R_{max} occurs when the spherical face of the probe tip fits the base of the valley of the cosine curve.

B.2 Maximum value of D

R_{max} is obtained using [Formula \(B.2\)](#):

$$R_{max} = \frac{R_{sm}^2}{2\pi^3 R_a} \quad (B.2)$$

Then, the maximum D value corresponding to R_{max} can be determined using [Formulae \(B.2\)](#) and [\(B.3\)](#):

$$D_{max} = 2(20 R_{max} - 100)^{0.5} \quad (10 \text{ nm} \leq R) \quad (B.3)$$

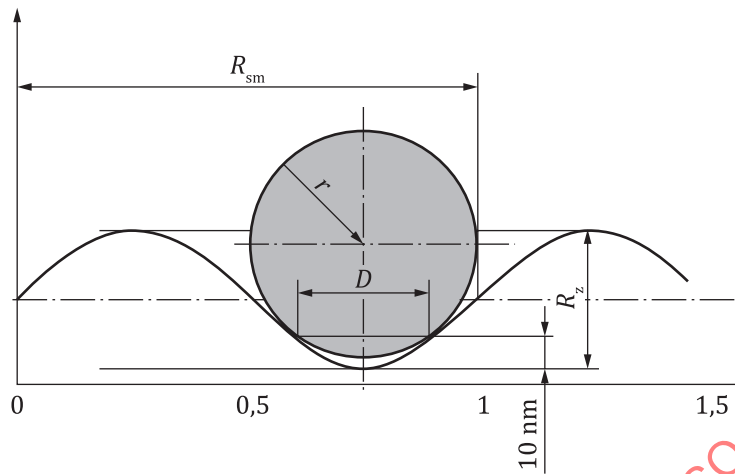
$$D_{max} = 2 R_{max} \quad (R < 10 \text{ nm}) \quad (B.4)$$

B.3 Comparison between calculations and measurements

D_{max} values calculated for specimens with $R_a = 5 \text{ nm}$ and 20 nm are shown in [Figures B.2](#) and [B.3](#), respectively. Open circles show D for probe tips used for a measurement. Measured R_a and its measurement error (ΔR_a) for a specimen with $R_a = 5 \text{ nm}$ are plotted in [Figure B.4](#). If it is assumed that the measured R_a using the sharpest probe tip in this experiment is real roughness, then it is found that ΔR_a is smaller than 5 % when D is smaller than $D_{max}/2$. When D is between $D_{max}/2$ and D_{max} , ΔR_a is smaller than 20 %. Measured R_a and ΔR_a for a specimen with $R_a = 20 \text{ nm}$ as plotted in [Figure B.5](#) show that ΔR_a is smaller than 3 % when D is about a half of D_{max} .

B.4 Determination of criteria

It is expected from the above description that ΔR_a is smaller than 5 % when D is smaller than $D_{\max}/2$ (5 % criterion) and ΔR_a is smaller than 20 % when D is between $D_{\max}/2$ and $D_{\max}$ (20 % criterion). Calculated $D_{\max}$ values for specimens with different R_{sm} are shown in [Figures 5](#) to [8](#).



Key

Y horizontal axis of roughness profile

Figure B.1 — Model for probe-tip error evaluation