Annex A: Uncertainty of measurement in the calibration of roughness standards

1 Introduction

For a contact stylus system according to ISO 3274 a model is set up according to which the values for the surface parameters are determined from the traced profile $z_e(x)$ via a chain of functions. For the calculation of the uncertainty of measurement in accordance with GUM, it is calculated in a chain of consecutive functions what effects the uncertainty of the input quantities has on the uncertainty of the result value after the respective function has been applied. The result then is the input quantity for the uncertainty calculation for the next function.

Value K of surface parameter *P* : K = P{Fc[Fs(G($z_e(x)$))]}

Function	Effect	Result
Explanation:		
Device function :	$G(z_e(x)) = z_g(x)$	data influenced by device function (total profile)
λs-filter:	$Fs(z_g(x)) = z_s(x)$	data influenced by λs (primary profile)
λc-filter:	$Fc(z_s(x)) = z_c(x)$	data influenced by λc (roughness profile)
Parameter function:	$P(z_c(x)) = K$	parameter function P calculates value K of surface parameter *P*

In this order the functions will in the following be dealt with.

2 Device function G

2.1 Description of model

The data of the total profile $z_e(x)$ are multiplied by a calibration factor C which is obtained from the calibration of the device against a calibrated depth-setting standard (reference standard type A) according to ISO 5436-1 (cf. Annex A, Figure 1).

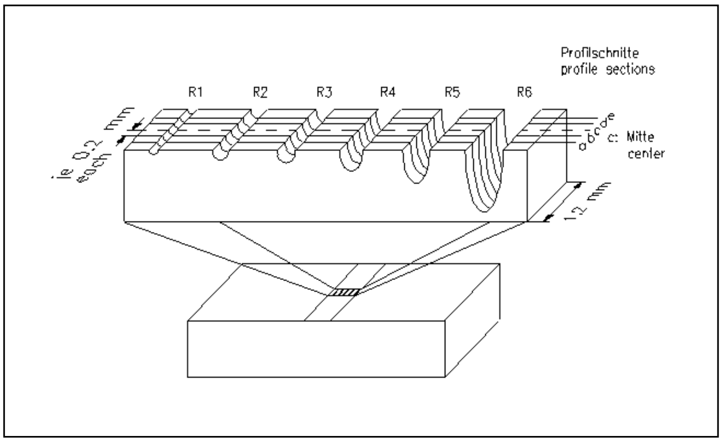

Figure 1: Depth-setting standard according to ISO 5436-1 with six grooves and measurement scheme for calibration

The total profile $z_g(x)$ covers the traced profile $z_e(x)$ (term according to ISO 3274) as well as influences stemming from the device, its interaction with the object to be measured and the environment. The values of the total profile $z_g(x)$ are the input data for signal processing. The following model is obtained:

$$z_g(x) = C \cdot [z_e(x) + z_{ref}(x) + z_0(x) + z_{pl}(x) + z_{sp}(x)] = C \cdot z_u \qquad (1)$$

where

C calibration factor

z_e traced profile

z_g total profile

z_{ref} profile of reference plane

z_0 background noise of device

z_{pl} profile deviation by plastic deformation of surface

z_{sp} profile variation due to stylus tip deviation

z_u uncorrected profile data

For the uncertainty of the profile points the following relation is obtained according to the product rule:

$$u^2(z_g) = u^2(C) \cdot z_u^2 + u^2(z_u) \cdot C^2 \qquad (2)$$

2.2 Calibration factor

2.2.1 Model for calibration factor

The calibration factor *C* is determined from the measured depth Pt_m or D_m, respectively, and the depth Pt_n or D_n, respectively, known from the calibration certificate for the depth-setting standard. The following model is valid:

$C = \frac{Pt_n}{Pt_m}$ rsp. $C = \frac{D_n}{D_m}$.

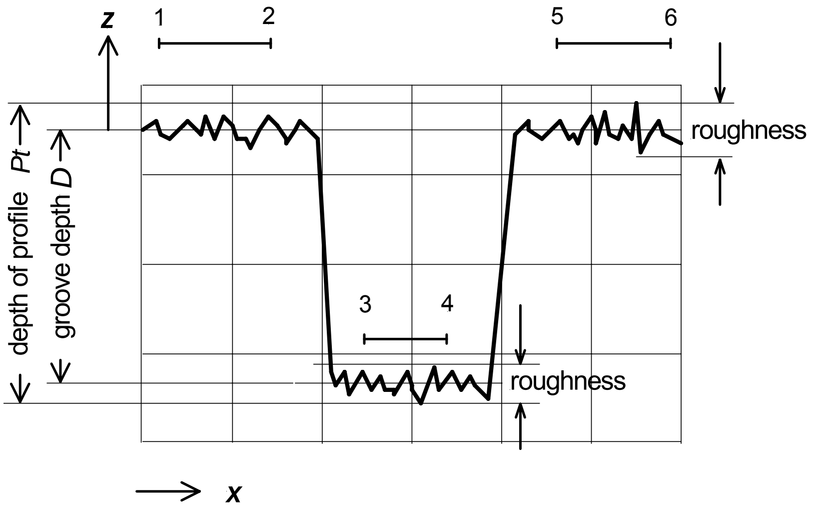

Figure 2: Profile evaluation on a depth-setting standard of type A1 (ISO 5436-1 and ISO 4287).
1-2, 5-6: profile line sections on reference plane, 3-4 profile line section in bottom of groove

The quantities in the numerator and in the denominator each are uncertain so that

$$u^2(C) = \frac{1}{Pt_m^4} \cdot \left[Pt_n^2 \cdot u^2(Pt_m) + Pt_m^2 \cdot u^2(Pt_n) \right] \qquad (3)$$

As $Pt_m \approx Pt_n$ is (*C* = 1), the following is obtained:

$$u^2(C) = \frac{1}{Pt_m^2} \cdot \left[u^2(Pt_m) + u^2(Pt_n) \right].$$

The first term of eq. 2 then is

$$u^2(C)\cdot z_u^2 = \frac{z_u^2}{Pt_m^2}\cdot\left[u^2(Pt_m)+u^2(Pt_n)\right].$$

Here it can be seen what effect results on the uncertainty of the calibration when a calibration groove is selected too small. The depth Pt_m of the reference standard is usually selected to the same amount as the expectation value z_u of the uncorrected profile points. Therefore the quotient $\frac{z_u^2}{Pt_m^2}=1$ is set and the first term of eq. 2 becomes

$u^2(C)\cdot z_u^2 = u^2(Pt_m)+u^2(Pt_n)$. Thus eq. 2 is transformed into

$$u^2(z_g) = u^2(Pt_m)+u^2(Pt_n)+u^2(z_u) \qquad (4)$$

$u^2(Pt_n)$ can be taken from the calibration certificate for the reference depth-setting standard.

2.2.2 Model for *Pt*m

For the measurement of the total height of profile Pt_m the place where the groove was calibrated is not exactly met. The measured total height of profile Pt_m contains Pt_n as well as a part ΔPt (Annex A Figure 3), which is position-dependent in the y-direction, and a component b describing the repeatability of the contacting process.

$$Pt_m = Pt_n + \Delta Pt + b$$

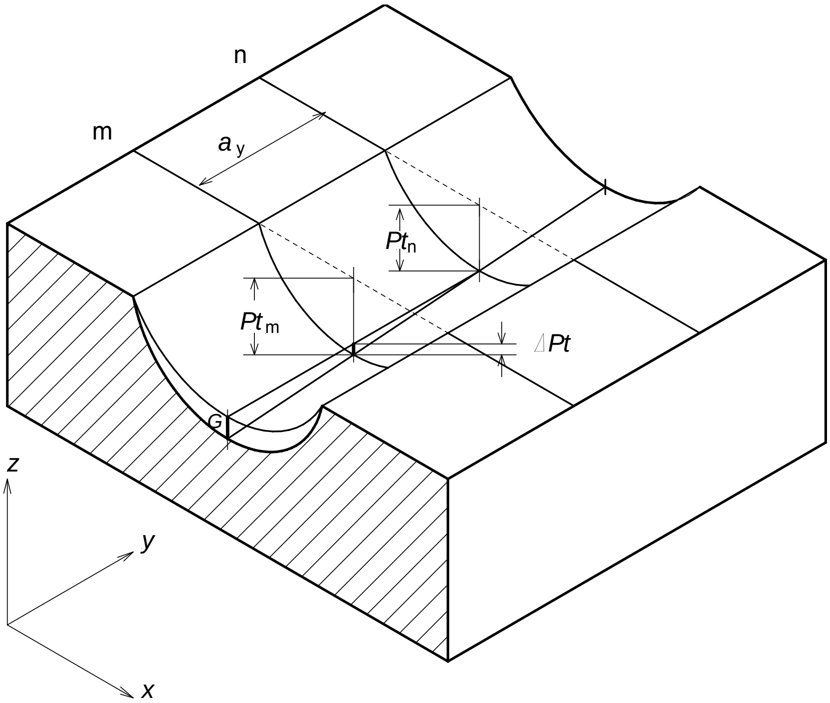

Figure 3: Uncertainty in the dissemination of the measure of depth

n: Trace for calibrating the groove,
m: trace during dissemination,
$a_y = y_n - y_m$: deviation of trace positioning,
$\Delta Pt = Pt_n - Pt_m$: deviation in determination of depth

The uncertainty of Pt_m is

$$u^2(Pt_m) = u^2(\Delta Pt) + u^2(b).$$

$u^2(b)$: repeatability of contacting process on calibration groove.

2.3 Uncertainty of total profile points

For the variance $u^2(z_g)$ of the measurement points of the total profile the following variances are obtained:

$u^2(z_g) =$

$u^2(Pt_n)$, variance of reference standard (depth-setting standard) (5.1)

$+u^2(\Delta Pt)$, variance of transfer from reference standard (5.2)

$+u^2(b)$, square of repeatability of tracing of reference standard (5.3)

$+u^2(z_e)$, square of uncertainty of obtained profile due to scatter on standard (5.4)

$+u^2(z_{ref})$, variance of reference profile (5.5)

$+u^2(z_0)$, variance due to background noise of device (5.6)

$+u^2(z_{pl})$, variance due to insufficient knowledge of plastic deformation (5.7)

$+u^2(z_{sp})$, variance due to insufficient knowledge of stylus tip geometry (5.8)

Chapter 3 gives numerical values or equations, respectively, for the calculation of these eight input quantities and describes the statistical properties of them. As they have different effects according to the parameter to be calculated and the type of standard, the input quantities relevant to the specific case are compiled and the overall uncertainty is determined. An example of the case without short wavelength filter λs is given in the table in section 7.1 and of the filtering with λs in section 7.2.

3 Determination of uncertainty of input quantities

3.1 Reference standard (depth-setting standard)

The uncertainty of measurement (U_n) of the total height of profile Pt_n of the reference standard is stated in the calibration certificate with the coverage factor k=2. This value is a statistically confirmed quantity. The empirical standard uncertainty therefore is:

$$u^2(Pt_n) = \frac{1}{4} \cdot U_n^2 .$$

Typical values are U_n = 10 nm at a groove depth of 250 nm to U_n = 50 nm at a groove depth of 10 µm.

3.2 Measuring trace

The determination of the groove depth in the calibration of the device does not necessarily take place at the same trace as in the calibration of the groove. Due to a gradient in the direction of the groove $G = \partial Pt/\partial y$, an uncertainty of the trace position in the y-direction leads to an uncertainty in depth measurement (Annex A Figure 3). Within $2a_y$, every point is equally probable.

$$u^2(\Delta Pt) = \frac{1}{3} \cdot \left(a_y \cdot G\right)^2$$

According to depth and quality of the groove, the gradient G has values between 10 nm/mm und 40 nm/mm.

3.3 Repeatability of contacting in calibration

The standard uncertainty by the repeatability of the contacting process during calibration is derived from the standard deviation of the mean value of m_w measurements of Pt_m in the calibration groove at the same point being $\frac{1}{\sqrt{m_w}} s(Pt_m)$.

So the variance due to the repeatability of the contacting process in calibration is

$$u^2(b) = s^2(\overline{Pt_m}) = \frac{1}{m_w} \cdot s^2(Pt_m) .$$

Gaussian distribution is assumed. For a typical number of repetitions m_w = 5 the distribution is poorly Gaussian, yet because of the small contribution of $s(\overline{Pt_m})$ to the combined uncertainty the effective degree of freedom of the latter remains large enough.

3.4 Topography of standard

In spite of its uniform structure in the y-direction (Annex A Figure 4), the standard also has a statistical nature.

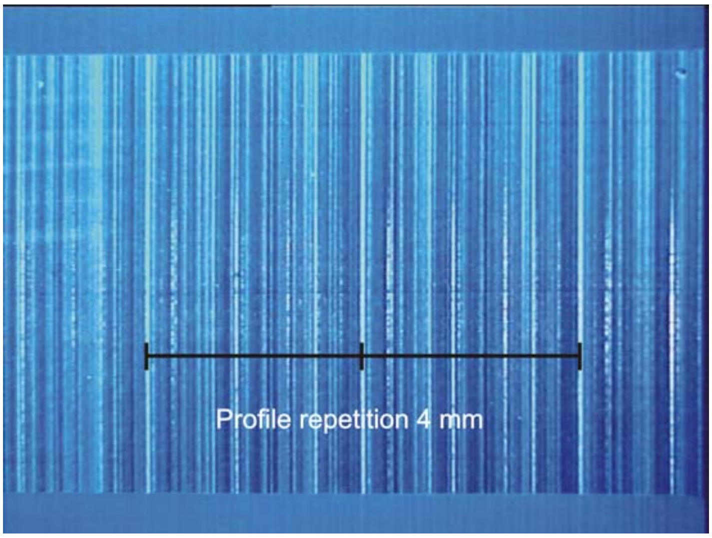

Figure 4: Type D1 roughness standard with profile repetition, DIN EN ISO 5436-1

Kommentar [KS1]: Foto in CDR-Zeichnung

This manifests itself by a statistical variation of the measured parameters in dependence on x and y. For the roughness standards this is taken into account in the measuring scheme (Annex A Figure 5) by spatial staggering of the measurements in the x- and y-directions.

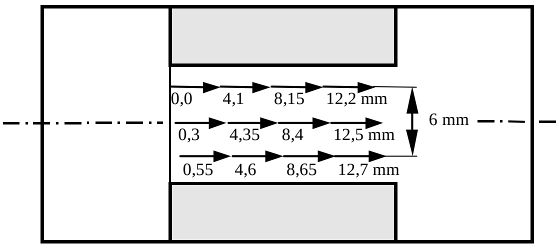

Figure 5: Measuring scheme for roughness standard (type D1, DIN EN ISO 5436-1)

For the number of profile sections, n = 12 is assumed. For the results Gaussian distribution is assumed.

In many evaluations the standard uncertainty of the individual values of the parameters is already frequently output. The standard deviation of the mean value $\frac{s(Rz)}{\sqrt{n}}$ can be taken as the estimated value for the uncertainty of the value of *Rz*. To obtain the uncertainty of the profile points needed here, it has to be taken into account that due to the averaging algorighm of *Rz* the uncertainty of *Rz* is smaller than the uncertainty of the profile points by the "smoothing factor" *S* of the algorithm. This is illustrated in chapter 6.

For the uncertainty component, eq. 5.4, of the overall profile, the following is obtained:

$$u^2(z_e) = \frac{1}{S^2} \cdot \frac{1}{n} \cdot s^2(Rz).$$

3.5 Straightness deviation

The term according to eq. 5.5 contains the uncertainty influences due to straightness deviations of the reference profile. The components of the long-wave deviations are dealt with in this section and those of the short-wave deviations in section 3.6.

The long-wave components of the straightness deviations are described in the W-profile by the parameter *Wt,* as well as drifts during the time of measurement. A measuring section on an optical flat is measured with that part of the feed unit which is also used for the subsequent surface measurement. It must be mechanically aligned in the best possible way. The measurements are repeated five times at the same area of the flat and of the guide. The mean value Wt_0 from five measurements – determined at λc = 0,8 mm – is further used. On the assumption of uniform distribution, the following is valid:

$$u^2(z_{ref}) = \frac{1}{3}\left(\frac{Wt_0}{2}\right)^2.$$

3.6 Background noise

When a profile is measured, the background noise produced by guiding as well as by electrical and mechanical influence quantities is directly superposed upon the measurement profile. This effect is measured separately when the noise Rz_0 is measured on a good optical flat. Experience has shown that an Rz_0 below 10 nm can be achieved on good flats using good tracing systems. By averaging of several of these profile sections, the time variation of the background noise is also covered. This is why the R-profile of the optical flat measurement is evaluated for the determination of the term in eq. 5.6. In doing so, it has to be ensured that this measurement covers that part of the feed unit which is subsequently used for carrying out the measuring point plan on the standard. The mean value from five measurements $\overline{Rz_0}$ is further used. To obtain the uncertainty of the profile points, the "smoothing factor" of the Rz algorithm must again be taken into account. On the assumption of a uniformly distributed quantity, the following is valid:

$$u^2(z_0) = \frac{1}{S^2} \cdot \frac{1}{12} \cdot \left(\overline{Rz_0}\right)^2 .$$

3.7 Plastic deformation

During tracing, plastic deformation of the surface results in dependence on material, tracing force and stylus tip radius. As long as the deformation produced during the calibration and the subsequent measurement is the same, it would be negligible. Due to inaccurate repetition of the tracing point and its spatial surface conditions (hardness, existing trace, etc.), the inexact knowledge of the plastic deformation is to be allowed for as an uncertainty component for the profile.

Experience with the usual conditions of measurement (stylus tip radius = 2 µm, tracing force = 0,7 mN, hardness of standard = 450 HV) has shown plastic deformations between the boundary values of 10 nm to 20 nm, i.e. within a span of $2a_{pl}$ = 10 nm /2/. On the assumption of a uniformly distributed quantity, the following holds for the term in eq. 5.7:

$$u^2(z_{pl}) = \frac{a_{pl}^2}{3}$$

3.8 Stylus tip radius

The term in eq. 5.8 has effects in the case of standards sensitive to the stylus tip geometry, i.e., for example, standards of type D according to DIN EN ISO 5436-1. The profile traced differs from the true surface due to the finite stylus tip radius. According to DIN EN ISO 3274, this influence of the stylus tip with the nominal radius is already a component of the traced profile for further evaluation. Deviations from the stylus tip radius stated in the calibration certificate result in uncertain z-positions.

The simulation for the tracing of the same profile with different stylus tip radii yielded the relations represented in Figure 6. For *Rz* and *Rz1max* a variation of -20 nm per 1 µm of variation of the stylus tip radius and for *Ra* a dependence of -5 nm/µm can be seen.

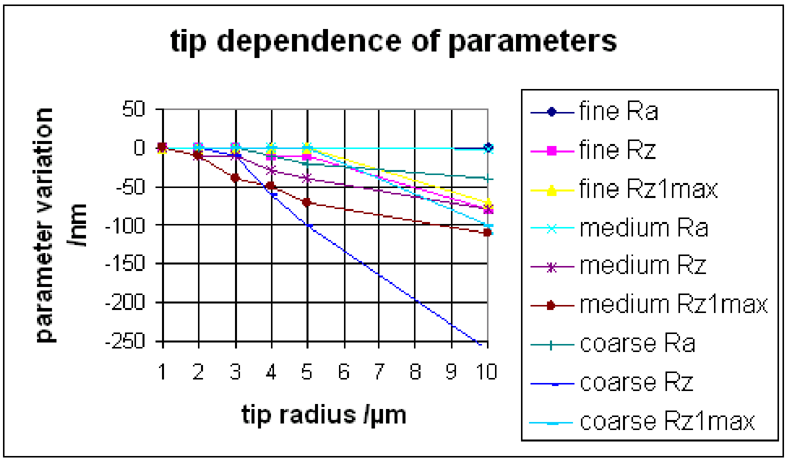

Figure 6: Dependence of the parameters on the stylus tip radius

Taking the "smoothing factor" of *Rz* into account, the following is obtained:

$$\frac{\partial z}{\partial r_t} = -\frac{1}{S} \cdot \frac{20\,\text{nm}}{\mu\text{m}}$$

The uncertainty of the stylus tip radius effective for the measurement is estimated at $u(r_t)$ = 1 µm and uniform distribution is assumed. The input quantity r is uncertain in the range r_{soll} ± 0,5 µm

$$u^2(z_{sp}) = \frac{1}{S^2} \cdot \frac{1}{3} \cdot \left(\frac{20\text{nm}}{\mu\text{m}} \cdot 0{,}5\mu\text{m} \right)^2 .$$

A compilation of the input quantities for the case without λs considered up to now is given in the table in section 7.1.

4 Short-wave low-pass filter λs

For the points z_s of the primary profile, the model in analogy to eq. 1 is valid, the reduction of the uncertainty of the λs-filtered primary profile data according to /1/ having an effect only on the profile data z_u currently measured:

$$z_s = Fs(z_g) = C \cdot Fs(z_u)$$

$$u^2(z_s) = u^2(C) \cdot Pt_n^2 + f_s^2 \cdot u^2(z_u) \qquad (6)$$

in the case of the ideal filter, with $f_s^2 = \frac{\Delta x}{\alpha \cdot \lambda s \cdot \sqrt{2}}$, Δx = sampling distance,

$\alpha = \sqrt{\frac{\log 2}{\pi}} = 0{,}4697$ and $\lambda_s =$ cutoff wavelength of the short-wave low-pass filter.

λs / µm	Δx / µm	f_s
2,5	0,5	0,55
8	1,5	0,53
8	0,5	0,31

At the values specified for λs and at the traversing lengths specified in DIN EN ISO 4287, the effect of the short-wave filter on the profile points thus is approximately equal: The uncertainty of the profile points of the filtered profile is reduced approximately by half. A compilation of the input quantities in this case is given in the table in section 7.2.

5 roughness cutoff filter λc

After the filtering with λc, the following is valid for the points of the waviness profile:

$u(w) = \sqrt{\frac{\Delta x}{\alpha \lambda c \sqrt{2}}} \cdot u(z_s) = f_c \cdot u(z_s)$ with ideal filter.

λc / µm	f_c
250	0,055

800	0,031
2500	0,017

The following are valid: for the points of the roughness profile: $z_c = z_s - w$,

for their uncertainty: $u^2(z_c) = u^2(z_s) - \left(2 \cdot \sqrt{2} - 1\right) \cdot u^2(w) \cong u^2(z_s)$.

Due to the small value of the uncertainty of the points of the waviness profile $u(w)$, the uncertainty of the points of the roughness profile $u(z_c)$ is practically equal to the uncertainty $u(z_s)$ of the points of the λs-filtered profile.

6 Parameter function

The points of the roughness profile $z_c(x)$ serve to calculate the value K of the parameter according to the algorithm of the parameter. The uncertainty u_{sys}(K) of a parameter can differ very strongly from the uncertainty of the profile points in dependence on their algorithm. This is described by, for example, $u_{sys}(Rz) = S(Rz) \cdot u(z_g)$, where *S(Rz)* is the "smoothing factor" of *Rz*. To show the influence of the algorithm, the effect of the algorithm of *Rz* is calculated as an example, uncorrelated profile data being assumed for simplification. For the averaged roughness depth *Rz* the following is valid:

$Rz = \frac{1}{5} \cdot \sum_{i=1}^{5} (p_i - v_i)$, where p_i and v_i are the maximum and minimum measurement values from five partial measuring sections. According to the sum rule, the uncertainty of the parameter is :

$$u^2(Rz) = \sum_{i=1}^{5} \left(\frac{\partial Rz}{\partial p_i} \right)^2 \cdot u^2(p_i) + \sum_{i=1}^{5} \left(\frac{\partial Rz}{\partial v_i} \right)^2 \cdot u^2(v_i) .$$

As $\frac{\partial Rz}{\partial p_i} = \frac{\partial Rz}{\partial v_i} = \frac{1}{5}$ is i for all,

$u^2(Rz) = \frac{1}{25} \left(\sum_{i=1}^{5} u^2(p_i) + \sum_{i=1}^{5} u^2(v_i) \right)$. As the uncertainties of the peak values $u(p_i) = u(v_i) = u(z_s)$ are equal to those of the individual values,

$u^2(Rz) = \frac{10}{25} \cdot u^2(z_s)$, or $u(Rz) = \sqrt{\frac{10}{25}} \cdot u(z_s) = \sqrt{\frac{10}{25}} \cdot f_s \cdot u(z_k)$, respectively.

As a result of the averaging effect of the algorithm of *Rz,* the uncertainty of the result quantity is smaller than the uncertainty of the profile points by the factor $S(Rz) = \sqrt{\frac{10}{25}}$.

7 Compilation of influence quantities

7.1 Without λs-filtering

In columns 4 and 7, typical values of the input quantities and their variance contributions are stated for a roughness standard with *Rz* = 3.

Section	Input quantity catchword	Calculation of input quantity	Exemplary values	Sensitivity coefficient	Method of determination, distribution	Variance [nm²]
3.1	Reference standard	$\frac{1}{4}\cdot U_n^2$	U_n = 15 nm (cal. cert.)	1	B Gaussian	
3.2	Difference measuring trace – calibration trace	$\frac{1}{3}\cdot\left(a_y\cdot G\right)^2$	a_y = 100 µm G = 20 nm/mm	G	B uniform	
3.3	Repeatability	$s^2(\overline{Pt_n})$	s = 3 nm	1	B Gaussian	
3.4	Topography	$\frac{1}{S^2}\cdot\frac{s^2(Rz)}{n\cdot}$	$s(Rz)$ = 50 nm	1	A Gaussian	
3.5	Straightness deviation	$\frac{Wt_0^2}{12}$	Wt_0 = 50 nm	1	B uniform	0
3.6	Background noise	$\frac{1}{S^2}\cdot\frac{1}{12}\cdot\left(\overline{Rz_0}\right)^2$	$\overline{Rz_0} = 20$ nm	1	A uniform	
3.7	Plastic deformation	$\frac{a_{pl}^2}{3}$	a_{pl} = 5 nm	1	B uniform	
3.8	Stylus tip	$\frac{1}{3}\cdot\frac{1}{S^2}\cdot\left(\frac{20nm}{\mu m}\cdot u(r_{sp})\right)^2$	$u(r_{sp})$ = 0,5 µm	-20 nm/mm	B uniform	

3.5 not applicable to R-parameters

3.7 not applicable to glass standards

If the complete equation for the systematic uncertainty component of *Rz* is formed, the following is obtained in the sum of column 3 in Table 7.1:

$$u_{sys}^2(Rz) = S^2 \cdot u^2(z_g) =$$

$$S^2 \times [\frac{1}{4} \cdot U_n^2 + \frac{1}{3} \cdot (a_y \cdot G)^2 + s^2(\overline{Pt_n}) + \frac{1}{S^2} \cdot \frac{s^2(Rz)}{n} + \frac{Wt_0^2}{12} + \frac{1}{S^2} \cdot \frac{1}{12} \cdot (\overline{Rz_0})^2 + \frac{a_{pl}^2}{3} +$$

$$\frac{1}{3} \cdot \frac{1}{S^2} \cdot \left(\frac{20nm}{\mu m} \cdot u(r_{sp}) \right)^2] \qquad (7)$$

As S is smaller than 1 and disregarding the input quantities which are regularly small, the following approximation can be made:

$$u_{sys}^2(Rz) \leq \frac{1}{4} \cdot U_n^2 + \frac{s^2(Rz)}{n} + \frac{Rz_0^2}{12}. \qquad (8)$$

7.2 With λs-filtering

In columns 4 and 7 typical values of the input quantities and their variance contributions are given for a roughness standard with *Rz* = 3.

Section	Input quantity catchword	Calculation of input quantity	Exemplary value	Sensitivity coefficient	Method of determination, distribution	Variance [nm²]
3.1	Reference standard	$\frac{1}{4}\cdot U_n^2$	U_n = 15 nm (cal.cert.)	1	B Gaussian	
3.2	Difference measuring trace – calibration trace	$\frac{1}{3}\cdot(a_y \cdot G)^2$	a_y = 100 µm G = 20 nm/mm	G	B uniform	
3.3	Repeatability	$s^2(\overline{Pt_n})$	s = 3 nm	1	B Gaussian	
3.4	Topography	$\frac{1}{S^2}\cdot\frac{s^2(Rz)}{f_s^2\cdot n\cdot}\cdot f_s^2$	$s(Rz)$ = 50 nm	1	A Gaussian	
3.5	Straightness deviation	$\frac{Wt_0^2}{12}\cdot f_s^2$	Wt_0 = 50 nm	1	B uniform	
3.6	Background noise	$\frac{1}{S^2}\cdot\frac{1}{12}\cdot\left(\frac{\overline{Rz_0}}{f_s}\right)^2\cdot f_s^2$	$\overline{Rz_0} = 20$ nm	1	A uniform	
3.7	Plastic deformation	$\frac{a_{pl}^2}{3}\cdot f_s^2$	a_{pl} = 5 nm	1	B uniform	
3.8	Stylus tip	$\frac{1}{3}\cdot\frac{1}{S^2}\cdot\left(\frac{20nm}{\mu m}\cdot u(r_{sp})\right)\cdot f_s^2$	$u(r_{sp})$ = 0,5 µm	-20 nm/mm	B uniform	

Remarks:

3.5 not applicable to R-parameters

3.7 not applicable to glass standards

If the complete equation for the systematic uncertainty component of *Rz* is formed, the following is obtained in the sum of column 3 in Table 7.2:

$$u_{sys}^2(Rz) = S^2 \times [\ \frac{1}{4}\cdot U_n^2 + \frac{1}{3}\cdot(a_y \cdot G)^2 + s^2(\overline{Pt_n}) + f_s^2 \times (\frac{1}{S^2}\cdot\frac{s^2(Rz)}{f_s^2 \cdot n \cdot} + \frac{Wt_0^2}{12} +$$

$$\frac{1}{S^2}\cdot\frac{1}{12}\cdot\left(\frac{\overline{Rz_0}}{f_s}\right)^2 + \frac{a_{pl}^2}{3} + \frac{1}{3}\cdot\frac{1}{S^2}\cdot\left(\frac{20nm}{\mu m}\cdot u(r_{sp})\right)^2)]\,. \qquad (9)$$

In accordance with the considerations in sections 3.4, 3.6 and 3.8, the estimated values for the uncertainties of the profile points are determined from the estimated values of the surface parameters and the smoothing effect of λs-filtering is taken into account

As *S* is smaller than 1 and disregarding the input quantities which are regularly small, the following approximation can be made:

$$u_{sys}^2(Rz) \le \frac{1}{4}\cdot U_n^2 + \frac{s^2(Rz)}{n} + \frac{Rz_0^2}{12}\,. \qquad (10)$$

This compilation is the same as in eq. 8, only with the difference that here λs-filtered estimated values are to be inserted.

8 Unknown systematic deviations

In the measuring chain systematic deviations can occur as a result of:

- the lack of conventions in the algorithms of the parameters in DIN EN ISO 4287
- permitted deviations in filters in DIN EN ISO 11562, e.g. by approximations in filter algorithms
- uncertainty due to linearity deviations of converter, bandwidth limitation for amplifier, resolution of A/D converter
- deviations of stylus tip from nominal form
- uncertainty of measuring points in the direction of feed.

For the uncertainty calculation unknown systematic deviations must therefore be taken into account for the functions. Software standards according to DIN EN ISO 5436-2 would allow these deviations to be more exactly localized. In the metrological practice, these uncertainties are discovered by comparison measurements, for example within the scope of intercomparisons, on materialized standards according to DIN EN ISO 5436-1, with different devices and different realizations of the algorithms, if possible. The standard deviations of the mean values of the parameters serve as estimated value for the uncertainties, the averaging having been made over the participating laboratories. These uncertainties $u_v(K)$ are compiled in a table in dependence on parameter, type of standard, range of measurement and filtering and are added quadratically to the systematic uncertainty.

$$u^2(\mathrm{K}) = u_{sys}^2(\mathrm{K}) + u_v^2(\mathrm{K})$$

The reference uncertainties u_v(parameter) are stated in the table in chapter 11.
The expanded uncertainty of measurement of the parameter (coverage probability = 95%) is

$$U(K) = 2 \cdot [\ \frac{1}{4} \cdot U_n^2 + \frac{s^2(Rz)}{n} + \frac{Rz_0^2}{12} + u_v^2(\mathrm{K})]^{1/2}$$

This derivation confirms the calculation practised at the calibration laboratories of the DKD, which has been obtained from experience.

For the determination of the smallest allowable measurement uncertainty the approximation from eq. 9 to eq. 10 is rather coarse. Especially for averaging parameters (S <<1) like Ra and Rq the weight of the first summand in eq. 9 is introduced with too much weight, because it is derived from not filtered data. This is taken into account by applying a more adequate averaging factor $S(\mathrm{K}) = \frac{\mathrm{K}}{Rz}$. K is representative for an estimate value of the considered parameter *Ra*, *Rq*, *Rpk*, *Rvk*, *Rk* , measured on a roughnes standard, whose roughness is measured as *Rz*.

$$U(\mathrm{K}) = 2 \cdot [\ \frac{1}{4} \cdot \frac{\mathrm{K}^2}{Rz^2} U_n^2 + \frac{s^2(\mathrm{K})}{n} + \frac{\mathrm{K}_0^2}{12} + u_v^2(\mathrm{K})]^{1/2}$$

9 Literature

/1/ M. Krystek:

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/2/ R. Krüger-Sehm, M. Krystek:

Uncertainty Analysis of Roughness Measurement

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10 Reference uncertainties

Table of reference uncertainties u_v for the uncertainty calculation at DKD laboratories, values in % of the measurement value, in accordance with RV 97

			Parameters **with** λs								Parameters **without** λs							
Type		λc in mm	Ra	Rz1max	Rz	Rk	Rpk	Rvk	Mr1	Mr2	Ra	Rz1max	Rz	Rk	Rpk	Rvk	Mr1	Mr2
GN	G	2,5	0,2	0,3	0,2						0,5	0,3	0,3					
	G	0,8	0,2	0,3	0,4						0,4	0,3	0,3					
	M	0,8	0,3	0,4	0,4						0,2	0,2	0,2					
	F	0,8	0,4	0,3	0,4						0,5	0,3	0,5					
	F	0,25	0,6	0,6	0,5						0,5	0,5	0,5					
Number of labs			**9**								**4**							
RN	Gg	2,5	0,5	0,6	0,7	0,3	0,3	0,6	0,2	0,1	0,4	0,5	0,3	0,1	0,1	0,3	0,1	0,1
	G	0,8	0,5	0,6	0,5	0,3	0,5	0,5	0,2	0,3	0,5	0,5	0,4	0,2	0,1	0,1	0,1	0,1
	M	0,8	0,4	0,3	0,5	0,7	0,3	0,3	0,4	0,2	0,5	0,5	0,1	0,4	0,1	0,2	0,1	0,1
	F	0,8	0,3	0,7	0,7	0,3	0,3	0,4	0,2	0,1	1,1	0,3	0,9	0,1	0,2	0,2	0,1	0,1
Number of labs			**7**								**5**							
SFRN	G	0,25	0,3	1,3	0,5	0,4	1,6	0,2	0,6	0,2	0,6	1,5	0,6	0,3	0,3	0,1	0,2	0,1

	M	0,25	0,3	1,2	0,8	0,5	2,1	0,3	0,4	0,1	0,4	0,8	0,7	0,4	0,2	0,2	0,1	0,1
	F	0,25	0,9	2,1	1,9	1,1	1,6	0,8	0,4	0,5	1	2,4	1,9	0,6	0,3	0,2	0,2	0,2
Number of labs			**6**								**4**							