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CALIBRATION OF THE VERTICAL MEASURING SYSTEM OF STYLUS INSTRUMENT PERTHOMETER S8P

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Original scientific paper

Measurement result without defined metrological traceability does not represent valid metrological information. National laboratory for length (HMI/FSB-LPMD), as constitutive part of Croatian Metrology Institute (HMI), has a responsibility to assure traceability using national and first line standards for length, roughness and angle. In HMI/FSB-LPMD traceability for roughness parameters is assured using calibrated National roughness standards. In this paper calibration of the vertical measuring system of stylus instrument Perthometer S8P using roughness standard is presented. Calibration has been performed according to the recommendations from *DKD Guideline 4-2.* Based on the model shown in *Directive DKD R 4-2, sheet 1, Annex A* measurement uncertainty of a roughness parameter *Rz* determined using Perthometer S8P has been evaluated.

Keywords: *calibration, metrological traceability, roughness standard, stylus instrument*

Umjeravanje vertikalne komponente elektroničko-mehaničkog uređaja s ticalom Perthometer S8P

Izvorni znanstveni članak

Mjerni rezultat bez definirane mjeriteljske sljedivosti ne predstavlja valjanu mjeriteljsku informaciju. Nacionalni laboratorij za duljinu (HMI/FSB-LPMD), kao konstitutivni član Hrvatskog mjeriteljskog instituta (HMI), ima zadaću osigurati sljedivost koristeći nacionalne i etalone prvog reda za duljinu, hrapavost i kut. U HMI/FSB-LPMD-u sljedivost u području ispitivanja hrapavosti osigurava se temeljem umjerenih nacionalnih etalona hrapavosti. U ovom radu prikazan je postupak provedbe umjeravanja vertikalne komponente elektroničko-mehaničkog uređaja s ticalom Perthometer S8P korištenjem etalona hrapavosti. Umjeravanje je provedeno u skladu sa smjernicama objavljenim u *DKD Guideline 4-2*. Na temelju matematičkog modela opisanog u *Directive DKD R 4-2, sheet 1, Annex A* procijenjena je mjerna nesigurnost parametra hrapavosti *Rz* izmjerena elektroničko-mehaničkim uređajem s ticalom Perthometer S8P.

Ključne riječi: *elektroničko-mehanički uređaji s ticalom, etaloni hrapavosti, mjeriteljska sljedivost, umjeravanje*

1 Introduction

An important task of metrology is to ensure metrological traceability. Traceability is a property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty. Traceability in testing surface roughness is oriented to 2D stylus instruments and established over several roughness parameters. ISO 5436-1:2000 recognizes five types of standards, and it is oriented to the following roughness parameters: *d, Ra, Rz* and *RSm*, [1].

Due to complexity of stylus measuring systems it is difficult to determine the measurement uncertainty. Until 2011 the expanded measurement uncertainty for stylus instruments was calculated according to the expression: $U = 2\sqrt{u(q)^2 + u_a^2}$, where $u(q)$ is the sample standard uncertainty estimate of the realized quantity and u_a is the uncertainty of the adjustment (correction of the systematic errors in the metrological characteristics), [2].

At the end of 2011 EURAMET TC-L has recommended the use of *DKD Guideline 4-2 Calibration of Devices and Standards for Roughness Metrology*, [3]. This document brings several calibration procedures for measuring instruments and standards for roughness measuring technique. This paper relies on a part of *Guide* that deals with calibration of the vertical measuring system of stylus instruments, *DKD-R 4-2 Sheet*, [4].

2 Calibration of the vertical measuring system of stylus instrument Perthometer S8P

The *DKD-R 4-2 Sheet 2* relies on traceability of parameter *Pt.* HMI/FSB-LPMD does not have a calibrated depth setting standard with specified value of that parameter. For this reason the calibration procedure for stylus instrument Perthometer S8P was carried out using only traceability from roughness standard, i.e. value of parameter *Rz*.

The calibration with depth setting standards establishes traceability to the national length standard, whereas the calibration with roughness standards validates the function of the complete transmission chain of the stylus instrument. Before calibration is carried out, correct functioning of the stylus instrument was checked in accordance with its operating instructions. The stylus instrument was calibrated at its place of use. This guarantees that the influences of the ambient conditions, which also prevail in the later use of the stylus instrument, are taken into account for the calibration.

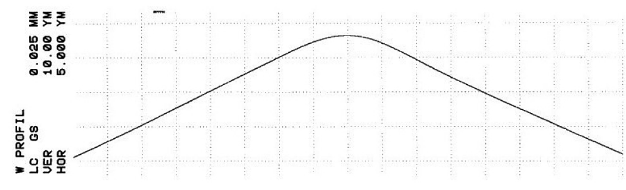

Figure 1 Recorded profile of a sharp protruding edge

Before calibration procedure the stylus condition was tested by traversing a sharp protruding edge (razor blade). Occurrence of irregularities in the graphical view of the recorded profile indicates that stylus is damaged [1]. The output profile (Fig. 1) represents that stylus tip used in calibration procedure was not damaged.

2.1 Admissibility for calibration

According to *DKD-R 4-2* the admissibility for calibration of stylus instrument must be determined for two calibration standards: depth setting standard and roughness standard.

Since HMI/FSB-LPMD does not have a calibrated *Pt* parameter the admissibility for calibration using depth setting standard was not conducted.

Calibration with a roughness standard was carried out in accordance with chapter 5.3. of *DKD-R 4-2 Sheet 2*. The device is suitable for roughness measurements if the results of the measurement of the roughness parameters on the reference standards deviate by less than their expanded measurement uncertainty plus a constant amount. If the deviation is smaller, the measurement uncertainty of the device calibration can be determined using roughness standards in accordance with chapter 6.3. of *DKD-R 4-2 Sheet 2*.

In order to assess the admissibility for calibration using Croatian national roughness standard (marked RET 132-280) parameter *Rz* has been measured. Obtained value of measured parameter *Rz* was:

$$Rz = 3{,}988\ \mu\text{m}. \tag{1}$$

In calibration certificate for roughness standard RET 132-280 the following is stated:

$$Rz = 3{,}97\ \mu\text{m},\ U = 0{,}20\ \mu\text{m};\ k = 2,\ P = 95\ \%. \tag{2}$$

Therefore the deviation of measured value from result expressed in calibration certificate is 0,018 μm. The sum of expanded measurement uncertainty and the constant (from experience amount of 1 % of the calibrated parameters) equals to:

$$U + const. = U + 1\ \%(Rz) = 0{,}20 + 0{,}0397 = 0{,}2397\ \mu\text{m} \tag{3}$$

The deviation of measured value from the result expressed in calibration certificate deviates by less than their expanded measurement uncertainty plus a constant amount:

$$deviation = 0{,}018\ \mu\text{m} < U + const = 0{,}2397\ \mu\text{m}. \tag{4}$$

Consequently, calibration of Perthometer S8P can be determined on the basis of roughness parameter *Rz* using roughness standard RET 132-280.

2.2 Calibration procedure

For calibration of Perthometer S8P the following types of standards were used:

- **Plane glass plate** is used for determination of basic noise.
- **Depth setting standard** is used for determination of the repeatability.
- **Roughness standard** is used to check the transmission chain function and to monitor the device properties (regular calibration).

Determination of basic noise. On a plane glass plate, Rz_0 was measured in five surface profiles under the measurement conditions used for the calibration of the device with roughness standards. The mean value is to be indicated in the calibration certificate as $\overline{R}_{z0}$.

Calculated mean value of roughness parameter $\overline{R}_{z0}$ determined in five surface profiles using stylus instrument Perthometer S8P equals:

$$\overline{R}z_0 = 13\ \text{nm}. \tag{5}$$

Determination of repeatability. The measurement on the depth setting standard was carried out for the profile depth which is important for the later use. The smallest possible measurement range which suits the profile depth was selected. The groove of depth setting standards was measured five times in the same position at a calibrated place in order to determine variance $s_w^2(Pt_m)$.

Before measurement was realized, the reference level of the standard was aligned horizontally with the aid of two partial ranges on the left and on the right of the groove by means of the least squares.

Calculated variance $s_w^2(Pt_m)$ determined at the same place on a depth setting standard in five surface profiles using stylus instrument Perthometer S8P equals:

$$s_w^2(Pt_m) = 12\ \text{nm}^2\ . \tag{6}$$

Fig. 2 presents profile depth on measured depth setting standard.

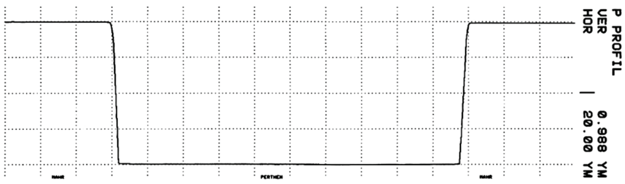

Figure 2 Recorded profile depth

Transmission chain function. On a roughness standard 12 profile sections were recorded on the measurement surface. The smallest possible measuring range suiting the roughness was selected (ISO 4288:1996) [5].

From the 12 profile sections, the arithmetic mean of the roughness parameters *Rz* was calculated and it equals:

$$\overline{R}z = 3{,}988\ \mu\text{m}. \tag{7}$$

Deviation of the determined mean value of the roughness parameters *Rz* from the value stated in the calibration certificate is 18 nm, or expressed relatively 0,45 %.

3 Measurement uncertainty of roughness parameter *Rz* determined using Perthometer S8P

Based on the model shown in *Directive DKD R 4-2, sheet 1, Annex A*, the uncertainty components which are influenced by the device properties and the calibration process are taken into account for the determination of the measurement uncertainty when stylus instrument Perthometer S8P is calibrated using roughness standard RET 132-280 [5] and [6].

The mathematical model:

$$U(Rz)=2\cdot\left[u_{RN}^2+\frac{1}{m_w}\cdot s_w^2(Pt_m)+\frac{1}{12}\cdot(\overline{R}z_0)^2+\right.$$
$$\left.+\frac{a_{\mathrm{pl}}^2}{3}+\frac{1}{3}\cdot(u(r_{sp}))^2\right]^{\frac{1}{2}}. \qquad (8)$$

where:

- u_{RN}^2 - standard uncertainty of the measurand on the reference standard (RS) used for device calibration. This also includes the determination of a possible amplification deviation. (**Traceability**)
- $\frac{1}{m_w}\cdot s_w^2(Pt_m)$ - probing repeatability of the device to be calibrated. The standard deviation s_w^2 of the mean value of the currently measured profile depth of the reference standard serves as an estimated value for m_w measurements of the profile depth Pt_m of the reference depth setting standard when the measurements are carried out at the same probing place. (**Repeatability**)
- $\frac{1}{12}\cdot(\overline{R}z_0)^2$ - **Basic noise** of the device to be calibrated.
- $\frac{a_{\mathrm{pl}}^2}{3}$ - **Plastic deformation** on the standard by stylus tip.
- $\frac{1}{3}\cdot(u(r_{sp}))^2$ - Influence of the **deviation of the stylus tip** from the nominal radius.

Traceability. The uncertainty of the measurand i.e. parameter *Rz* on used roughness reference standard RET 132-280 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:

$$u_{RN}=\frac{u_{RN}}{k}=100\ \mathrm{nm}. \qquad (9)$$

Repeatability. 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:

$$s_{\overline{x}}=\frac{1}{\sqrt{m_w}}\cdot s_w(Pt_m). \qquad (10)$$

Calculated variance $s_w^2(Pt_m)$ determined at the same place on a depth setting standard in five surface profiles using stylus instrument Perthometer S8P equals:

$$s_w^2(Pt_m)=12\ \mathrm{nm}^2. \qquad (11)$$

The variance due to the repeatability of the contacting process in calibration amounts:

$$s^2(\overline{Pt_m})=\frac{1}{m_w}\cdot s_w^2(Pt_m)=29\ \mathrm{nm}^2. \qquad (12)$$

Basic 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. By averaging of several of these profile sections, the time variation of the background noise is also covered. Obtained mean value calculated from five measurements $\overline{R}z_0$ was:

$$\overline{R}z_0=13\ \mathrm{nm}. \qquad (13)$$

On the assumption of a uniformly distributed quantity, the following is valid:

$$u^2(z_0)=\frac{1}{12}\cdot(\overline{R}z_0)^2=14\ \mathrm{nm}^2. \qquad (14)$$

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 $2a_{\mathrm{pl}}$ = 10 nm, [5].

Hardness on the surface for RET 132-280 standard equals:

- hardness of silicon: 1223 HV ± 30,3 HV
- hardness of silicon dioxide: 1360 HV ± 90,1 HV.

In addition to the specified hardness, tip radius of 2 μm and measuring force of 1,3 mN, the value of plastic deformation a_{pl} is assumed to be 5 nm. On the assumption of a uniformly distributed quantity, the following holds:

$$u^2(a_{\mathrm{pl}})=\frac{a_{\mathrm{pl}}^2}{3}=8\ \mathrm{nm}^2. \qquad (15)$$

Stylus tip radius. The profile traced differs from the true surface due to the finite stylus tip radius. 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.

In preformed calibration procedure of Perthometer S8P 2 µm stylus tip was used and *R*z parameter was measured, therefore parameter variation equals −20 nm / µm. [5]

Standard uncertainty of stylus tip radius, assuming uniform distribution therefore is:

$$u^2(z_{sp}) = \frac{1}{3}\cdot\left[u(r_{sp})\right]^2 = 33\,\mathrm{nm}^2. \tag{16}$$

By adding up the components of standard uncertainties the overall variance of stylus instrument Perthometer S8P equals:

$$u^2_{\mathrm{device}}(Rz) = 10\,084\,\mathrm{nm}^2. \tag{17}$$

Tab. 1 shows the influence quantities for Perthometer S8P calibration on the basis of roughness parameter *Rz*. By multiplying combined standard uncertainty with coverage factor *k* = 2, expanded measurement uncertainty of the stylus instrument Perthometer S8P calibration for determination of the roughness parameter *Rz* equals:

$$u_{\mathrm{device}}(Rz) = 201\ \mathrm{nm},\ k = 2;\ P = 95\ \%, \tag{18}$$

i.e. relative standard uncertainty is expressed as:

$$u_{\mathrm{rel}}(\mathrm{device}, RN) = \frac{u_{\mathrm{device}}(Rz)}{Rz}\cdot 100 = 2{,}5\,\%. \tag{19}$$

Table 1 Uncertainty budget of the Perthometer S8P calibration for determination of the roughness parameter *Rz*

Input quantity	Calculation of the input quantity	Value for Rz = 3,97µm	Sensitivity coefficient	Distribution	Variance, nm^2
Traceability	u^2_{RN}	$U_{RN}(Rz)$ = 0,20 µm, from the cal. cert. of RS => u = 100 nm	1	Gaussian	10 000
Repeatability	$\frac{1}{m_w}\cdot s^2_w(Pt_m)$	s_w = 12 nm m_w = 5 repeat. measurements	1	Gaussian	29
Basic noise	$\frac{1}{12}\cdot(\overline{R}z_0)^2$	$\overline{R}z_0$ = 13 nm	1	Uniform	14
Plast. deform.	$\frac{a^2_{\mathrm{pl}}}{3}$	a_{pl} = 5 nm	1	Uniform	8
Stylus tip	$\frac{1}{3}\cdot(u(r_{sp}))^2$	$u(r_{sp})$ = 2 µm	−20 µm	Uniform	33
Device, totally	Sum column above	$u^2_{\mathrm{device}}(Rz)$			10 084
Relative standard uncertainty	$u_{\mathrm{device}}(Rz)/Rz$	u_{rel}(device, RN)			2,5 %

4 Conclusion

By publishing *Directive DKD Guideline 4-2* several calibration procedures for measuring instruments and standards for roughness measuring technique have been presented. The research in this paper relies on the guidelines from *DKD-R 4-2 Sheet 2: Calibration of the vertical measuring system of stylus instruments*. In that document two calibration standards are used; depth setting standard and roughness standard. The calibration with depth setting standards establishes traceability to the national length standard, whereas calibration with roughness standards validates the function of the complete transmission chain of the stylus instrument.

Since HMI/FSB-LPMD does not have a calibrated depth setting standards the calibration procedure for stylus instrument Perthometer S8P was carried out using only traceability from roughness standard, i.e. value of parameter *Rz*.

In *DKD-R 4-2 Sheet 2* procedures for calculation of measurement uncertainty in the calibration of stylus instruments using depth setting standards and roughness standards are stated as well.

In this paper verified relative standard uncertainty of roughness parameter *Rz* determined using Perthometer S8P equals 2,5 %.

In order to fully meet the guidelines from the document *DKD-R 4-2 Sheet 2* in the next calibration of standards for roughness metrology HMI/FSB-LPMD will request the calibration of a parameter *Pt* on depth setting standard as well.

5 References

[1] ISO 5436-1:2000 Geometrical Product Specifications (GPS) -- Surface texture: Profile method; Measurement standards -- Part 1: Material measures

[2] ISO 12179:2000 Geometrical Product Specifications (GPS) -- Surface texture: Profile method -- Calibration of contact (stylus) instruments

[3] DKD Guideline 4-2: Calibration of measuring instruments and standards for roughness measuring technique (2011)

[4] DKD-R 4-2 Sheet 2: Calibration of the vertical measuring system of stylus instruments (2011)
[5] Directive DKD R 4-2, Sheet 1, Annex A: Calibration Sheet 2: Uncertainty of measurement in the calibration of roughness standards instruments (2011)
[6] Medić, S.; Runje, B. Validation of the realised measurement uncertainty in process of precise line scales calibration. // Tehnicki vjesnik-Technical Gazette, Vol. 19 (2012), pp 331-337.

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