A novel traceability route to the SI in roughness measurements at IPQ

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ABSTRACT
A new traceability methodology for roughness stylus calibration is being developed in the National Metrology Laboratory of the Portuguese Institute for Quality (IPQ) using a high-precision displacement transducer. The calibration and dissemination of roughness standards measurements is one of the activities of IPQ. A stylus instrument is used to acquire the height values of the scanned points on the surface of the roughness standard. Defined according to ISO standards, namely the ISO 21920-2:2021, the integrated software calculates the roughness parameters that quantify the surface. A set of roughness parameters, measured after stylus calibration with different standards artefacts, as defined in ISO 5436-1:2000 has been evaluated. The need for the development of a new route for the metrological traceability in roughness, with faster calibration and better accuracy was also analyzed. The use of a displacement transducer, as reference, was the studied solution.

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1. INTRODUCTION

The manufacture of equipment and products implies the knowledge of technical parameters, among which the metrological requirements of surfaces roughness are included. Contact stylus instruments are used by metrology laboratories for characterizing surface roughness. In the profilometer, instrument used for measurement of a surface profile, the probing system, usually called "pick up" consist of the stylus, the pivot, the probe, and the digitizing system [1] and are the main components of the equipment for the surface scanning. During a measurement, the stylus runs along the surface with a predefined force and at a constant speed. The height of the peaks, hills, dales, and pit are detected and converted into a signal during the measurement by the probe or transducer component of the instrument.

The line traversed on the surface by the stylus is converted into the set of points, $Z(x)$, that characterize its profile. With this type of instruments, it is possible to measure the surface height irregularities up to several hundred of micrometers, with resolutions at the nanometric level. According to the ISO 12179: 2021 [2], the stylus instruments metrological traceability is obtained by the measurement of calibrated artifacts.

Due to an increased demand by the industry in terms of dynamic properties, precision, and larger measurement rates, a new route to SI unit meter definition was analysed involving the possibility of including the traceable displacement generators as reference for the stylus instruments calibration. Ongoing displacement generators studies were developed to characterize accuracy and linearity of the steps measured. Findings on this are crucial to define how stand-alone devices can be used for contact probes and stylus calibration. In this matter, along with internal research IPQ is also participating on the European Metrology Programme for Innovation and Research (EMPIR), in the ProbeTrace project [3].

This paper describes the roughness stylus instrument calibration with different reference standards (depth setting, gauge blocks and displacement transducer) and compares the measurement results of two surfaces obtained after each calibration. The roughness main supporting normative documents are also mentioned, as well as IPQ calibration and measurement capabilities available.

In the following section, the importance of surface topography characterization is presented, as well as the description of the measurement system, used both is industry and metrology laboratories. Section 3 describes the comparison

procedure, the equipment and the two standards used in the roughness stylus calibration, as indicated in ISO 5436-1, as well as the results obtained. In section 4 an alternative method for traceability in roughness measurements is described using displacement transducers as reference standards. The conclusion presents the results and identifies improvements using the displacement transducer.

2. SURFACE TOPOGRAPHY CHARACTERIZATION

A manufactured surface is a geometrically non-ideal surface, presenting shape defects produced by the mechanical characteristics of the equipment used in the manufacturing. For example, in metal-cutting, the surface may present waves due to the rotation of the cutting tool and roughness depending on the shape of the saw teeth.

The final product must meet tight dimensional tolerances, to assure conformity of the parts. The manufacturer must carry out measurements of the parts produced with a high accuracy and reproducibility to identify those within the specified tolerance.

There are several methods to perform a topography measurement, namely stylus profilometry and optical scanning. In industry, the predominant roughness measuring instruments are the stylus instruments, which use the profile method.

To ensure that roughness measurement requirements are met, the stylus equipment must be calibrated, in the working environment, through rapid metrologically traceable processes and with low uncertainties measurements.

2.1. Stylus instrument

At IPQ laboratory, the roughness measurements were performed by a Mahr Perthometer stylus instrument, consisting of a computer connected to a drive unit with the pick-up attached. The high-precision drive unit is a long-distance instrument for lengths up to 60 mm with an accuracy of 0.2 μm allowing the assessment of form deviations like waviness and roughness. The constant tracing speed can be adjusted to either 0.1 mm/s or 0.5 mm/s. The stylus tip senses the heights and valleys of the surface by the contacting force characteristic of the pick-up selected. An example of a pick-up used is present in the Figure 1.

The pick-up of the Mahr Perthen programme is inductive and the traced line is converted into an electronic signal. The digitized signal is filtered and represents the primary surface profile $Z(x)$, nevertheless, other filters can be added (for instance the ISO 16610-21:2011 [4] and ISO 16610-30:2015 [5]), and the waviness and roughness profile can also be displayed, see Figure 2.

With the concrete type of stylus instruments, IPQ provides the calibration of roughness standards to the industry customers, for the roughness parameters listed in the Table 1, supported through IPQ participation at international comparisons EURAMET.L-K8.2013 - Calibration of surface roughness standards [6].
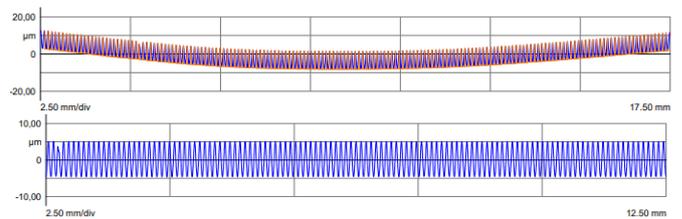

Figure 1. Pick-up and drive unit.

Figure 2. Lines profiling examples generated for profile and waviness (P-W profiles) and roughness (R-profile).

2.2. Roughness standard documents

The ISO/TC 213/WG 16 - Areal and Profile Surface Texture, is the working group under the technical committee ISO TC213 - Dimensional and Geometrical Product Specifications and Verification, responsible for creating, updating, and maintaining the ISO Geometrical Product Specifications (GPS) standards, related to surface properties.

Documents linked to the key parts of roughness measurement, namely: the vocabulary, the measurement standards, the measurement methods, the general structure, the calibration, and applications of contact (stylus) instruments; may be identified, at ISO and at other National Standardization Bodies and Institutes. In Table 2 a list of ISO-published standards from ISO TC213 is presented as the most significant documents internationally used in topographic surface analysis.

The American standard ASME B 46.1: 2009 [7] is a complete standard document on surface texture with 12 sections with contents such as: Terms Related to Surface Texture; Classification of Instruments for Surface Texture Measurement; Terminology and Measurement Procedures for Profiling, Contact, Skidless Instruments; Measurement Procedures for

Table 1. IPQ roughness measurement types provide, and parameters ranges supported by an international comparison.

Measurement types	Roughness Parameter: range
Depth standard ISO 5436-1 type A2	depth d: 0,1 μm to 10 μm
Roughness standard ISO 5436-1 type C	Ra: 0,1 μm to 10 μm Rz, Rp, Rv, Rt: 0,1 μm to 20 μm
Roughness standard ISO 5436-1 type D	Ra: 0,1 μm to 10 μm Rz, Rp, Rv, Rt: 0,1 μm to 20 μm

Table 2. ISO TC213 published standards for roughness measurement.

Standard	Geometrical product specifications (GPS) - Surface texture:
ISO 12179: 2021	Profile method - Calibration of contact (stylus) instruments.
ISO 25178-601:2010	Areal — Part 601: Nominal characteristics of contact (stylus) instruments
ISO 25178-701: 2010	Areal —Part 701: Calibration and measurement standards for contact (stylus) instruments.
ISO 3274:1996	Profile method - Nominal characteristics of contact (stylus) instruments.
ISO 21920-1: 2021	Profile — Part 1: Indication of surface texture
ISO 21920-2: 2021	Profile — Part 2: Terms, definitions, and surface texture parameters
ISO 21920-3: 2021	Profile - Part 3: Specification operators
ISO 5436-1: 2000	Profile method; Measurement standards - Part 1: Material measures.
ISO 8785:1998	Surface imperfections - Terms, definitions, and parameters.

Contact, Skidded Instruments, among others. This standard also gives the specifications and procedures for precision reference specimens. The information reported was adopted from the ISO 5436-1:2000 [8], but this standard provides nominal values for the specifications of the measurement standards (depth, height, width for Type A1, depth and radius for type A2).

The fundamentals, the set-up, the measuring conditions, and the procedure for roughness measurement by the profile method using stylus instruments are also described in the German VDI/VDE 2602-2:2018 [9]

The quantitative assessment of the surface texture can be obtained by the evaluation of the single profile through the 2-D surface texture in connection with filters [10]. According to ISO 21920-2: 2021 [11] the surface texture analysis involves the primary, the waviness, and the roughness profiles. This document [ISO 21920-2: 2021] is the most used standard for quantification of surface texture and in it, all the field parameters related to the evaluation length (le) used for identifications of the geometrical structures, are defined. The distribution of the peaks and pits, characterises the waviness and roughness of the surface. The document also identifies a list of field parameters that includes the height, the spatial, the volume, and hybrid parameters all related to the evaluation length. Furthermore, a list of feature parameters is also indicated, for instance the based on peak heights and pit depths. Out of the 53 parameters from ISO 21920-2:2021, 2 were selected for the present study, Ra and Rt parameters, because their nominal values, generally, characterize the roughness standards used to guarantee metrological traceability and according to their great use in the fabrication process.

Arithmetic mean height

R_a (equation (1)) is the arithmetic mean of absolute value of the ordinate value

$$R_a = \frac{1}{l_e} \int_0^{l_e} |Z(x)| \mathrm{d}x \,. \tag{1}$$

Total height

R_t (equation (2)) is the sum of the largest height and the largest depth

$$R_t = \max_{x \in X}\big(z(x)\big) - \min_{x \in X}\big(z(x)\big) \,, \tag{2}$$

where $X = \{x \in \mathbf{R} | 0 \le x \le l_e\}$.

3. ROUGHNESS MEASUREMENT PROCEDURE

At the laboratory, two different surface textures were selected, with two types of roughness, Mitutoyo with a random profile and Mahr with a sinusoidal profile. These surfaces have uniaxial marks oriented in one direction and were used for the comparison of the measured R_a and R_t parameters, after the calibration of the Z-axis stylus instrument with different reference standards.

3.1. Equipment and reference standards

The stylus instrument Mahr Perthen (S8P) with a 50 µm vertical range was the unit used for the performance of all surface measurements. The stylus tip possesses a nominal radius of 2 µm with a total cone angle of 90° and with a contact force of 0.4 mN.

For the stylus instrument vertical profile component $Z(x)$ axis calibration, following equipment was used:

1) a calibrated depth standard Type A. A glass surface typically characterized by a wide rectangular groove with a flat bottom.
2) two calibrated gauges blocks grade K. The selected gauge blocks were cleaned to remove any rust and wringing to a highly flat surface to stays tightly adhered.

These reference standards and their metrological characteristics are listed in Table 3.

For the measurement after S8P calibration, two surface textures were used:

a) one with random profiles and R_a = 3.05 µm as nominal value (hereinafter referred to as Mitutoyo).
b) another with periodic profiles and R_a = 2.3 µm as nominal value (hereinafter referred to as Mahr).

3.2. Roughness traceability with depth standard

The traceability to the unit length was, in the first place, done by the calibration of the stylus S8P vertical component, $Z(x)$ axis, with the calibrated depth standard type A. Following the technical procedure of the manufacturer, the glass groove with a flat bottom and a nominal depth of 9.1 µm, was measured by the stylus S8P (Figure 3.a)) and compared with the reference value (Table 3) producing a correction value that is automatically introduced in the software. In such a manner, the calibration of the $Z(x)$ axis stylus instrument is completed.

After the calibration, two surfaces were placed, one at a time, and the measurements were conducted by the stylus instrument. Twelve measurements distributed over these two surfaces were performed with a section length, l_{sc} = 2.5 mm, and an evaluation length, l_e = 12.5 mm, using a Gaussian filter. The measurement values for the roughness parameters R_a and R_t, showed in Table 4: Z-axis calibrated with depth standard (ds), corresponds to the average value of the twelve measured profiles of each surface.

3.3. Roughness traceability with gauge block

Secondly, the stylus S8P vertical component, Z(x) axis, was calibrated with a step generated by two calibrated gauge block grade k, with a nominal height of 9.0 µm (Figure 3.b)). According to their last calibration certificates (Table 3) a step with 8.9 µm was generated and used. A new and corresponding correction value was evaluated and automatically introduced in the stylus S8P software, and the calibration was concluded.

The Mitutoyo and Mahr surfaces were again measured at the same section length and the R_a and R_t parameters evaluated. The values measured, V_{gb}, after this calibration with gauge blocks (gb) are also presented in Table 4.
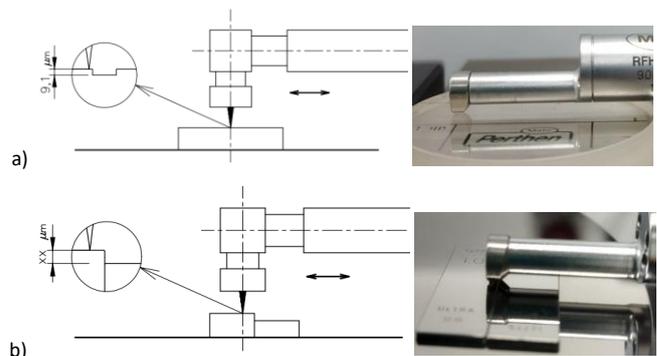

Figure 3. Vertical profile component calibration with a) depth measurement standard and b) gauge blocks.

Table 3. Reference standards and their calibration values with expanded uncertainties, U (k = 2).

Reference standard	Class	Quantity Nominal value	Reference value from the calibration certificate (Measured value ± U)
Depth standard	Type A1 (ISO 5436-1:2000)	Step d = 9.01 μm	d = (9.05 ± 0.05) μm
Gauge block	Grade K (ISO 3650:1998)	Height $h1$ = 1.001 mm $h2$ = 1.01 mm	h = (1.001069 ± 2.0 · 10^{-5}) mm (1.009994 ± 2.0 · 10^{-5}) mm

Table 4. Roughness surface measurement results (After Stylus Z-axis calibrated with depth standard and gauge blocks).

Surface (profile)	Height parameter	Nominal value in μm	Z-axis calibrated with depth standard (ds)		Z-axis calibrated with gauge blocks (gb)		$\lvert V_{ds} - V_{gb} \rvert$ in μm	E_n
			Vds in μm	U (k = 2) in μm	Vgb in μm	U (k = 2)in μm		
Mahr (Sinusoidal)	R_a	2.3	2.310	0.06	2.335	0.06	0.02	0.2
	R_t	7.9	7.97	0.15	8.01	0.09	0.04	0.2
Mitutoyo (Random)	R_a	3.05	3.100	0.06	3.086	0.06	0.01	0.1
	R_t	9.9	10.10	0.50	9.96	0.17	0.14	0.3

3.4. Measurement uncertainty considerations

From the measurement process described in the previous sections, and from the general principles of the stylus instrument probing process as indicated at the VDI/VDE 2602-04 [12] several sources of uncertainty were identified. The uncertainty budget was evaluated according to the Guide to the expression of uncertainty in measurement (GUM) [13]. The concrete approach for expression of the influence quantities, according to the type-A and type-B evaluation principles, was adopted. The main uncertainty sources considered were:

a) Standard uncertainty of the reference standard, u_r (equation (3))

$$u_r = \sqrt{\frac{U_r}{k}}, \qquad (3)$$

where U_r and k are given in the calibration certificate of the reference standard.

b) Standard uncertainty of the process of transferring the value of the reference standard to the sensing system, $u(C)$ (calibration factor (C), equation (4)).

$$u(C) = \sqrt{\left(\frac{1}{dm^2} \times \left[u^2(dm_{repr}) + u^2(Dn) \right] \right)}, \qquad (4)$$

where dm is the average of 5 measurements performed on the reference standard, and $u(dm_{repr})$ the corresponding standard deviation.

c) Background noise of the stylus instrument; $u(Zn)$ (determined by measuring the Rz_0 parameter on an optical flat), equation (5).

$$u(Zn) = \sqrt{\frac{\overline{(Rz_0)}^2}{12}}, \qquad (5)$$

where $\overline{Rz_0}$ is the average of 12 measurements made on the reference standard, in static mode (without movement of the stylus system through the surface).

d) Reproducibility of the measurement value of the parameter, $u(Rx)_r$ (assessed at each surface calibration from the n = 12 profiles acquired), equation (6).

$$u(Rx)_r = \sqrt{\frac{s^2(Rx)_r}{n}}, \qquad (6)$$

where x is the measured value of a parameter X, for example, R_z.

In this study, the uncertainty evaluation of the surface measured differs only in the estimated value of the degree of influence due to the reference standard (Depth-setting standard type A or gauge block) used in the Z-axis stylus instrument calibration.

3.5. Roughness measurement results

The measured surfaces (Mitutoyo and Mahr) have roughness textures, for the R_t parameter between 7.9 μm to 9.9 μm. In Table 4, the measured values, as well as the expanded uncertainties, calculated by multiplication of the standard uncertainties with a coverage factor of k = 2 are listed. The V_{ds} is the measured value obtained after the calibration of the $Z(x)$ axis stylus instrument when the depth standard (ds) was used as a reference standard. The V_{gb} is the value obtained after the $Z(x)$ axis stylus instrument calibration with gauge blocks (gb).

The results show that the difference between the measured values $V_{ds} - V_{gb}$ are within the uncertainty values, as confirmed by the evaluation of the respective Normalized Error $E_n \leq 1$ [14] as expected. Thus, as expected, the results are compatible. The measurement uncertainty differs according to the reference standard used in the calibration of the stylus instrument, which is the source of uncertainty that most dominantly influences that difference, once that the measured surface is homogeneous and linear.

As the calibration uncertainty of the depth standard type A used is 50 nm and that of the standard blocks is 20 nm as shown in Table 3, the measurement uncertainties (Table 4) reflect this fact, namely in the measurement of the Rt parameter.

Thus, the use of reference standards, with lower calibration uncertainties, is one of the developments to be studied and implemented.

4. DISPLACEMENT TRANSDUCERS AS ROUGHNESS REFERENCE STANDARDS

IPQ ongoing investigation of new methods to calibrate stylus instruments with contact probes is being held within the scope of the European R&D project, ProbeTrace.

The ProbeTrace consortium is constituted by the National Metrological Institutes of Turkey (TUBITAK), Italy (INRIM), Spain (CEM), Poland (GUM), Portugal (IPQ), Serbia (DMDM), Croatia (FSB), Bulgaria (BIM), Egypt (NIS), and Saudi Arabia (SASO-NMCC). IPQ investigates the implementation of portable displacement generators (PZT) for application in the

field of calibration of stylus instruments, with the smallest uncertainty value as possible. The PZT is a piezo stage with a capacitive sensor design that offers nanometric performance in a compact package with a different travel (100 µm to several millimetres) allowing sub-nanometre resolution and high linearity with good accuracy. From Aerotech's QNP series single-axis piezo nanopositioning stages a PZT with a resolution of 0.90 µm and a travel of 600 µm was selected.

For establishment of the metrological traceability the PZT was first calibrated using a linear interferometer. The PZT control program allowed the generation of linear displacements with steps of 0.316 µm (half the wavelength of the laser used) and their comparison with the indication of the interferometer, allowing their calibration with low uncertainty.

The parallelism between the direction of the PZT movement and the direction of the interferometer arm was a critical factor that required alignment studies.

4.1. Roughness traceability with PZT

The reference standard is supposed to be as accurate as possible, and it has to possess adequate long-term stability and reproducibility. The concrete requirements are fulfilled by the depth standard and gauge block artifacts. But a reference standard must also follow scientific evolution, and the PZT technical specifications make it a good candidate for a reference standard in surface characterization.

Without changing the method for the measurement of the surface texture, keeping the stylus instrument and procedure, a new approach for their calibration was performed with the use of the Aerotech PZT.

Figure 4 represents the scheme and image of the measuring system implemented in the laboratory for the calibration of the stylus equipment, where the PZT is used to generate the step/s.

The correction factor for the calibration of stylus profilometer (S8P) using piezo Aerotech (QNP60Z-500 Single-Axis, Z Piezo nanopositioning Stage, 500 µm travel) with a generate step of 9.5 µm was evaluated and stored in the stylus software. The surface texture Mitutoyo was measured, and the comparison of these roughness measurement values with that obtained after the calibration of S8P using ISO 5436 Type A1 present a difference value of 0.015 µm and an appropriate correspondence with $E_n \leq 0.4$.

5. CONCLUSIONS

The measurement of the roughness height parameters, R_a and R_t show metrological compatibility of measurement results when the stylus instrument is calibrated by depth standard or gauge blocks. With the concrete equipment, the expanded measurement uncertainty possesses a value of 60 nm for the R_a parameter.
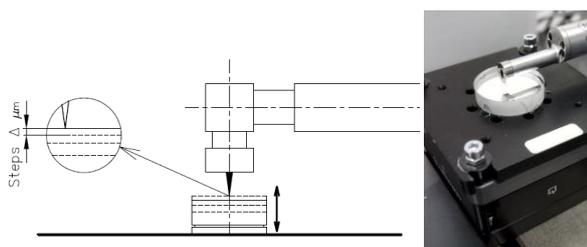

Figure 4. Scheme and image for the calibration of the stylus equipment vertical profile component with PZT.

The improvements expected with the use of portable PZT's as working measurement standard in the roughness measurement traceability chain is currently being developed at IPQ length laboratory.

The metrological characteristics of the PZT and the work performed until now, shows that this type of PZT is a good possibility for improvement of the measurement uncertainty stated by IPQ in this type of calibrations. Also, with the PZT it is possible to generate accurate and different steps height.

Further studies are now in progress: the optimization of the alignment, and the participation in an international comparison to validate this new method.

These experiments also indicate that the developments in new measurement methods have a coherent path and open new possibilities in the ability to determine the metrological characteristics of the equipment available in the industry and will bring new possibilities and services to customers.

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