

# Reproducibility of Areal Topography Parameters Obtained by Atomic Force Microscope

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**Abstract:** In the context of quality management and Industry 5.0, reproducibility is a critical indicator of the ability to achieve consistent and predictable results in laboratories, research, as well as in systems and processes. Reproducibility is also an indispensable component of measurement uncertainty, which quantifies the precision of measurement results. To standardize the measurement procedure for surface topography parameters obtained using atomic force microscope (AFM) and to establish the accuracy and precision of measurement results, an analysis of repeatability and reproducibility was conducted in accordance with the ISO 5725-2:2019 standard, Accuracy (trueness and precision) of measurement methods and results – Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method. Measurements were performed on two AFM standards and a steel sample. The research was conducted over the course of one year and repeated after four years using the same samples.

**Keywords:** areal topography parameters; atomic force microscope; Industry 5.0; quality management; reproducibility

## 1 INTRODUCTION

In the contemporary context of quality management and the development of Industry 5.0, the reproducibility of measurement results represents a critical parameter for ensuring consistency and predictability across various domains of scientific research, laboratory testing, and complex industrial and technological systems. The reproducibility of measurement results has become to be a fundamental aspect of quality management in diverse industries, particularly during the transition to Industry 5.0, where human-machine collaboration and advanced technologies are take center stage.

International standards such as ISO 5725 – Accuracy (trueness and precision) of measurement methods and results [1] and ISO 21748:2017 – Guidance for the use of repeatability, reproducibility and trueness estimates in measurement uncertainty evaluation [2] provide guidelines for assessing the accuracy and precision (repeatability, reproducibility) of measurement methods. Accurate and precise measurement data are crucial for implementing technologies such as IoT and big data analytics in Industry 4.0. These standards also offer a framework for evaluating and managing measurement uncertainty, ensuring high-quality standards in personalized manufacturing characteristic of Industry 5.0. Integrating ISO 5725 and ISO 21748:2017 into measurement processes ensures that decisions are based on accurate, reliable, and comparable data, which is essential for successful business operations and research. The analysis of repeatability and reproducibility in accordance with ISO 5725 is conducted across various fields and branches of science, including measurement system analysis [3], chemistry [4], medicine [5] and others.

Surface topography as one of the main indicators of surface quality plays a key role in determining the mechanical, tribological, biological, optical and other product properties [6]. The development of technologies has increased the requirements for surface quality, and thus the need for three-dimensional (areal) measurement techniques and surface characterization [7]. Surface topography testing is performed using different methods and a wide array of

linear and areal topography parameters [8]. The first devices for measuring the topography, i.e. the roughness of the technical surface were stylus instruments, and they were developed in the 1930s [9]. The surface topography test using a stylus instrument with a probe is carried out by means of the probe tip, which makes contact with the tested surface and moves along the direction of measurement. With a stylus instrument, line (2D) profile measurement is performed, which provides some functional data on the surface. However, areal or three-dimensional (3D) measurement is required to fully characterize functional surface information [10]. The development of the white light interferometer and the 3D non-contact profilometer in the early 1980s enabled areal measurement of surface topography [11]. The non-contact profilometer, operating on the principle of light interference, is currently the most commonly used optical device. Today, due to increasingly stringent surface quality requirements, surface topography testing is also conducted using scanning microscopes, in addition to the traditional methods mentioned above. Scanning microscopes, in order to obtain information on surface topography, are divided into scanning electron microscopes and microscopes with scanning probes. The scanning electron microscope operates by directing an electron beam focused by an electromagnetic field. Microscopes with scanning probes create an image of the surface by using a probe that touches the surface for data collection [12]. Among microscopes with scanning probes, the atomic force microscope (AFM) stands out, enabling the display of surface topography in both 2D and 3D.

It can be concluded that today numerous methods and instruments have been developed that are used for testing and analysis of surface topography [13]. All these methods, both traditional and modern, require clear protocols for the calibration of measuring instruments and internationally recognized standards that define measurement conditions, criteria for input values in measurement procedures, parameters that characterize the surface, procedures for evaluating measurement uncertainty, and so on. These methods rely on entirely different measurement principles, so without a clearly defined instrument calibration procedure, measurement procedure, and result analysis, achieving compatibility between results obtained from different

methods is unlikely. There are a large number of standards in the field of surface topography measurement, and new standards are currently under development. The aim of these developing standards is to achieve harmonization in the field of surface topography measurement. The objective of this study is to determine the stability (repeatability and reproducibility) of measurement results obtained by AFM in the field of surface topography.

## 2 AREAL TOPOGRAPHY PARAMETERS

Surface topography is a three-dimensional characteristics of a surface that provides a quantitative insight into the condition of the surface, and includes components of surface texture (roughness and waviness) and other irregularities, such as deviations from the shape [14].

The parameters describing surface topography can be categorized into line (2D) and areal (3D) parameters. Line parameters are derived from data collected along a single line, based on the surface profile. Depending on the type of profile, the line parameters can be designated as *P* for primary profile, *W* for waviness profile, and *R* for roughness profile. According to the ISO 4287:1997 standard, "Geometrical Product Specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters," line roughness parameters are classified into four main groups: amplitude, spacing, hybrid, and curve-related parameters.

Areal topography parameters quantitatively describe the condition of the surface of the measured sample and are designated as marked *S* or *V* [3]. Parameters marked with the label *S* describe the scanned area, while those labeled *V* indicate the material volume per unit area [15]. These are commonly referred to as 3D topography or roughness parameters in the literature. Unlike line parameters, the initial letter of the surface parameter label does not indicate the type of surface observed (roughness or waviness). For example, the parameter *Sa* can be applied to roughness, waviness, or primary profile data [3]. In order to unambiguously interpret the results, it is necessary to indicate which filter was used next to the areal topography parameter. To unambiguously interpret the results, it is important to specify the filter used alongside the areal topography parameter.

Table 1 Areal topography parameters

Arithmetical mean height	$Sa = \sqrt{\frac{1}{A} \iint_A  z(x, y)  dx dy}$
Root mean square height	$Sq = \sqrt{\frac{1}{A} \iint_A  z^2(x, y)  dx dy}$
Maximum height	<i>Sz</i>

There are numerous surface topography parameters that are needed to fully describe the surface condition. According to the ISO 25178-2:2021 standard, Geometrical product specifications (GPS) – Surface texture: Areal – Part 2: Terms, definitions and surface texture parameter [16], areal topography parameters are grouped into several categories: height, spatial, hybrid, functional, related, and miscellaneous parameters. To gain a comprehensive understanding of the surface's condition, it is essential to monitor as many areal

topography parameters as possible. Tab. 1 provides the expressions used to calculate the areal surface topography parameters measured in this study.

## 3 REPEATABILITY AND REPRODUCIBILITY OF MEASUREMENT RESULTS

The paper analyses the repeatability and reproducibility of areal topography parameters *Sa*, *Sq* and *Sz* obtained by the atomic force microscope (Oxford MFP-3D Origin). Prior to conducting the measurements, the AFM was calibrated using the STS3-1000P standard, developed by the American company VLSI Standards. The selected scan size is 20 μm × 20 μm, the scan resolution is 256, and the scan speed is 80 μm s<sup>-1</sup>. Areal topography parameters *Sa*, *Sq* and *Sz* measured by the atomic force microscope were measured on the primary surface, i.e. they were not filtered. Measurements were performed on two AFM standards and a steel sample. The standards and sample are presented in 2D and 3D view in Figs. 1, 2 and 3.

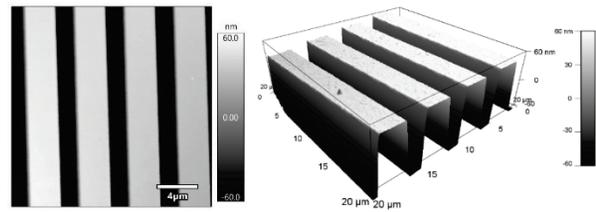


Figure 1 Standard 1 in two-dimensional and three-dimensional form

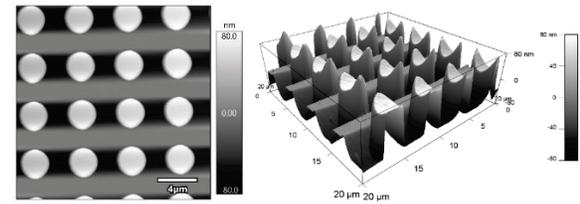


Figure 2 Standard 2 in two-dimensional and three-dimensional form

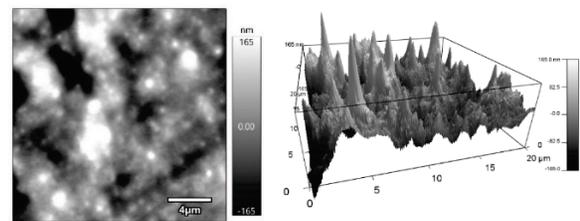


Figure 3 Sample in two-dimensional and three-dimensional form

The calculation of repeatability and reproducibility of measurement results was performed in accordance with ISO 5725-2:2019 standard, Accuracy (trueness and precision) of measurement methods and results – Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method [17]. Definitions of basic terms and expressions for the calculation of repeatability and reproducibility in accordance with ISO 5725-2:2019 are provided in Tab. 2. In accordance with ISO 5725 standard, repeatability and reproducibility are assessed on the basis of comparative measurements between laboratories. In this paper, the theory of comparative measurements is applied to measurements within one laboratory. The term laboratory has

been replaced by the term measuring series, and refers to a change in the measurement conditions (e.g. a change in the measuring point on a standard or object of measurement). The analysis was performed to determine the precision and compatibility of measuring devices and methods.

**Table 2** Definitions of basic terms and expressions

<b>Repeatability</b> Precision under repeatability conditions. Conditions where independent test results are obtained with the same method on identical test items in the same laboratory by the same operator using the same equipment within short intervals of time.	
<b>Reproducibility</b> Precision under reproducibility conditions. Conditions where test results are obtained with the same method on identical test items in different laboratories with different operators using different equipment.	
Terms	Expressions (Formulae)
The arithmetic mean of test results $x_{ij}$ in the $i^{\text{th}}$ measurement series. $n$ – number of repeated measurements Index $i$ represents the measurement series ( $i = 1, 2, \dots, m$ ) Index $j$ represents the measurement in the measurement series ( $j = 1, 2, \dots, n$ )	$\bar{x}_i = \frac{1}{n} \sum_{j=1}^n x_{ij}$
Grand mean of test results $N$ – total number of measurements	$\bar{x} = \frac{1}{N} \sum_{i=1}^m \sum_{j=1}^n x_{ij}$
The estimate of the within-measurement series standard deviation.	$s_i = \sqrt{\frac{\sum_{j=1}^n (x_{ij} - \bar{x})^2}{n_i - 1}}$
Repeatability standard deviation	$s_r = \sqrt{\frac{\sum_{i=1}^m (n_i - 1) s_i^2}{\sum_{i=1}^m n_i - 1}}$
The estimate of the between-measurement series standard deviation.	$s_L = \sqrt{s_d^2 - \frac{s_r^2}{n}}$
The estimate of the standard deviation of the mean of measurement series	$s_d = \sqrt{\frac{\sum_{i=1}^m (\bar{x}_i - \bar{x})^2}{m - 1}}$
Reproducibility standard deviation	$s_R = \sqrt{s_r^2 + s_L^2}$
Repeatability limit – with a probability of 95 %.	$r = 2.8s_r$
Reproducibility limit – with a probability of 95 %.	$R = 2.8s_R$

In order to calculate the repeatability and reproducibility of areal topography parameters  $Sa$ ,  $Sz$  and  $Sq$ , 15 repeated measurements were performed on the standards in two measurement series. Within the measurement series, measurements were performed under repeatability conditions (same metrologies, same measuring instrument, same measurement conditions, repeating measurements in a short period of time). Between the measurements performed in the first and second measurement series (measurements performed in two days), the repeatability conditions were not fully met, but the reproducibility conditions were entered.

In order to examine the influence of surface quality (uniformity) on the reproducibility of areal parameters of surface topography, measurements were performed on standards and steel sample. Measurements were performed in five measuring series (different measuring points) with three repeated measurements. The term different measuring points refers to three repeated measurements performed at five

distinct locations on a single standard or sample. The conducted statistical tests did not reveal outliers in the measurement results.

The comparison of results was conducted using the  $En$  agreement factor (Eq. (1)), where  $n$  represents the number of laboratories participating in the study.

$$En = \frac{|\bar{x}_1 - \bar{x}_2|}{2\sqrt{u_1^2 + u_2^2}} \leq 1 \tag{1}$$

The measurement uncertainties of areal topography parameters were evaluated by mathematical models in [15], and are equal to  $u(Sa) = 2.2$  nm,  $u(Sz) = 3.5$  nm,  $u(Sq) = 2.4$  nm.

#### 4 ANALYSIS OF MEASUREMENT RESULTS

The analysis results of repeatability and reproducibility of areal topography parameters  $Sa$ ,  $Sz$  and  $Sq$  performed on standards in two measurement series of which each contained fifteen repeated measurements. Results are shown in Tables 3 and 4. The measured values of repeatability  $r$  and reproducibility  $R$  are the values within which it can be expected that there is a difference between two individual measurement results, obtained under the conditions of repeatability and reproducibility with probability  $P$ . The tables present the results measured in 2021 and four years later, in 2025.

**Table 3** Standard 1 – two measurement series

	$Sa/\text{nm}$		$Sz/\text{nm}$		$Sq/\text{nm}$	
	Measurement series					
2021	1	2	1	2	1	2
	50.85	50.16	174.52	175.91	54.65	54.39
$s_i$	0.15	0.22	1.40	1.59	0.47	0.20
$\bar{x}$	50.50		175.22		54.52	
$r$	0.528		4.133		0.995	
$R$	0.567		4.433		1.027	
2025	Measurement series					
	1	2	1	2	1	2
$\bar{x}$	50.24	51.24	182.50	176.63	51.812	53.71
$s_i$	0.16	0.19	2.03	1.63	0.174	0.244
$\bar{x}$	50.74		179.63		52.76	
$r$	0.489		5.094		0.586	
$R$	0.593		5.394		0.881	
$En$	0.04		0.44		0.26	

The absolute difference of two individual measurement results of parameters  $Sa$ ,  $Sz$  and  $Sq$ , under repeatability and reproducibility conditions will in no more than 5 % of cases be greater than  $r$  and  $R$ . For example: The absolute difference of two individual measurement results of parameters  $Sa$  and  $Sq$  under reproducibility conditions will in no more than 5 % of cases be greater than 1 nm. The absolute difference of two individual measurement results of parameters  $Sz$  under reproducibility conditions will in no more than 5 % of cases be greater than 6 nm. The results showed that by repeating the measurements after a long period of time we did not enter the reproducibility conditions, ie that the time period between

measurements does not significantly affect the areal topography parameters  $Sa$ ,  $Sz$  and  $Sq$ .

**Table 4** Standard 2 – two measurement series

	$Sa/nm$		$Sz/nm$		$Sq/nm$	
	Measurement series		Measurement series		Measurement series	
2021	1	2	1	2	1	2
$\bar{x}$	28.87	28.28	205.54	203.21	40.61	40.00
$s_i$	0.17	0.17	1.27	1.68	0.17	0.18
$\bar{\bar{x}}$	28.57		204.37		40.30	
$r$	0.468		4.114		0.477	
$R$	0.498		4.114		0.509	
2025	Measurement series		Measurement series		Measurement series	
	1	2	1	2	1	2
$\bar{x}$	30.88	30.69	205.30	210.03	41.52	41.811
$s_i$	0.28	0.12	1.42	1.98	0.28	0.12
$\bar{\bar{x}}$	30.79		207.67		41.67	
$r$	0.592		4.763		0.595	
$R$	0.592		4.902		0.595	
$En$	0.36		0.33		0.21	

**Table 5** Standard 1 – five measurement series ( $Sa/nm$ )

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	51.24	51.59	52.38	51.5	50.99
$s_i$	0.03	0.08	0.06	0.03	0.06
$\bar{\bar{x}}$	51.54				
$r$	0.148				
$R$	1.460				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	50.47	49.73	51.45	52.08	51.78
$s_i$	0.17	0.05	0.05	0.08	0.05
$\bar{\bar{x}}$	51.10				
$r$	0.257				
$R$	2.711				
$En$	0.07				

**Table 6** Standard 1 – five measurement series ( $Sz/nm$ )

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	198.3	159.9	170.1	189.1	173.2
$s_i$	1.00	0.79	0.25	1.12	1.17
$\bar{\bar{x}}$	178.20				
$r$	2.572				
$R$	24.616				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	140.09	191.49	215.10	173.31	163.63
$s_i$	3.12	1.25	2.61	4.40	1.01
$\bar{\bar{x}}$	176.72				
$r$	3.664				
$R$	29.665				
$En$	0.15				

The analysis of the results of repeatability and reproducibility of areal topography parameters  $Sa$ ,  $Sz$  and  $Sq$  were performed on standards in a set of five measurement series of which each contained three repeated measurements. Results are shown in tables 5 to 10.

The analysis was conducted to determine the impact of surface quality (uniformity) on reproducibility of areal topography parameters.

The results showed that the change of the measuring point on the standards does not significantly affect the areal topography parameters  $Sa$  and  $Sq$ . The absolute difference of two individual measurement results of parameters  $Sa$  and  $Sq$  under reproducibility conditions will in no more than 5 % of cases be greater than 1 nm.

**Table 7** Standard 1 – five measurement series ( $Sq/nm$ )

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	54.29	54.66	55.12	54.64	54.27
$s_i$	0.03	0.07	0.08	0.06	0.07
$\bar{\bar{x}}$	54.59				
$r$	0.180				
$R$	0.971				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	53.54	53.70	55.08	55.18	54.17
$s_i$	0.14	0.11	0.11	0.21	0.18
$\bar{\bar{x}}$	54.34				
$r$	0.423				
$R$	2.134				
$En$	0.04				

**Table 8** Standard 2 – five measurement series ( $Sa/nm$ )

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	28.69	29.34	29.7	28.69	28.61
$s_i$	0.02	0.06	0.03	0.04	0.02
$\bar{\bar{x}}$	29.01				
$r$	0.106				
$R$	0.786				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	30.49	30.98	31.11	30.86	30.14
$s_i$	0.11	0.11	0.19	0.24	0.29
$\bar{\bar{x}}$	30.71				
$r$	0.558				
$R$	1.183				
$En$	0.24				

**Table 9** Standard 2 – five measurement series ( $Sz/nm$ )

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	198.3	205.4	209.3	203.6	203.8
$s_i$	0.20	0.26	0.26	0.29	0.12
$\bar{\bar{x}}$	204.11				
$r$	0.644				
$R$	6.343				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	242.96	293.54	212.61	190.67	188.74
$s_i$	0.43	0.37	0.40	0.26	0.29
$\bar{\bar{x}}$	205.7				
$r$	0.986				
$R$	23.879				
$En$	0.16				

The change of the measuring point on the standard 2 introduced the conditions of reproducibility, ie the change of the measuring point significantly effects the areal topography parameter  $Sz$ . The absolute difference of two individual measurement results of parameter  $Sz$  under reproducibility conditions will in no more than 5 % of cases be greater than 25 nm.

The analysis results of repeatability and reproducibility of areal topography parameters  $Sa$ ,  $Sz$  and  $Sq$  were performed on sample in five measurement series of which each contained three repeated measurements. Due to its irregular surface, the measurement uncertainty of the topography parameters is higher than that of the reference standards. Results are shown in Tabs. 11 to 13.

**Table 10** Standard 2 – five measurement series ( $Sq/nm$ )

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	40.07	39.56	39.53	39.46	40.37
$s_i$	0.04	0.02	0.01	0.03	0.03
$\bar{x}$	39.80				
$r$	0.077				
$R$	1.111				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	41.30	41.78	41.82	41.64	41.52
$s_i$	0.16	0.11	0.08	0.17	0.13
$\bar{x}$	41.61				
$r$	0.368				
$R$	0.654				
$En$	0.27				

**Table 11** Sample – five measurement series ( $Sa/nm$ )

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	62.84	124.3	111.7	90.7	102.1
$s_i$	0.35	0.49	1.49	0.18	1.01
$\bar{x}$	98.33				
$r$	2.362				
$R$	64.635				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	104.85	93.60	80.64	97.80	112.33
$s_i$	0.28	0.20	1.24	0.75	1.61
$\bar{x}$	97.85				
$r$	2.711				
$R$	33.148				
$En$	0.08				

**Table 12** Sample – five measurement series ( $Sz/nm$ )

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	749.42	992.88	1020.85	757.35	01247.12
$s_i$	0.40	14.41	21.48	3.08	3.72
$\bar{x}$	913.52				
$r$	32.521				
$R$	408,40				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	1101.07	722.90	650.18	816.32	1164.33
$s_i$	9.50	5.83	3.52	16.31	8.16
$\bar{x}$	890.96				
$r$	26.772				
$R$	634.61				
$En$	0.97				

Based on the analysis of repeatability  $r$  and reproducibility  $R$  performed on the sample, it can be concluded that the change of the measuring point on the sample introduced the conditions of reproducibility, i.e. that the change of the measuring point significantly effects the areal topography parameters.

According to the ISO 21748: 2017 standard, Guidance for the use of repeatability, reproducibility and trueness estimates in measurement uncertainty evaluation [2], one of the input values in the mathematical model for evaluating measurement uncertainty is the reproducibility of measurement results. The standard deviation  $s_R$  is expected to be estimated from comparative measurements. In this paper, the theory of comparative measurements is applied to measurements within one laboratory, and the term different laboratories refers to a change in the measurement conditions (e.g. change of the measuring point on the object of measurement).

**Table 13** Sample – five measurement series ( $Sq/nm$ )

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	83.93	173.3	145.9	113.2	102.8
$s_i$	0.3	0.81	1.74	0.08	2.95
$\bar{x}$	123.82				
$r$	4.359				
$R$	35.659				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	129.60	118.71	101.72	123.03	132.56
$s_i$	0.19	0.14	1.09	0.63	1.33
$\bar{x}$	121.12				
$r$	2.278				
$R$	33.578				
$En$	0.40				

The difference in repeatability and reproducibility values before and after four years for measurements of two measurement series across all measured parameters is less than 1 nm. For measurements of five measurement series on Standards 1 and 2, the difference in repeatability and reproducibility before and after four years is less than 2 nm for the  $Sa$  and  $Sq$  parameters and less than 4 nm for the  $Sz$  parameter. The values of the  $En$  agreement factor for all measurements on Standards 1 and 2 before and after four years are less than 1, indicating that the results are compatible. Differences in repeatability and reproducibility before and after four years for the measurement sample, can be attributed to the non-uniform surface of the measurement sample.

## 5 CONCLUSION

Ensuring high repeatability and reproducibility of measurement results is a fundamental prerequisite for effective quality management and the advancement of Industry 5.0. Reliable measurement data are essential for integrating advanced manufacturing technologies, including artificial intelligence-driven quality control, cyber-physical systems, and data-driven process optimization. The principles of ISO 5725 and ISO 21748 provide a robust framework for evaluating measurement accuracy and precision, supporting enhanced decision-making in intelligent manufacturing ecosystems. The increasing reliance on digitalization and automation in Industry 5.0 underscores the need for standardized measurement methodologies to ensure process stability, minimize variability, and achieve high precision in next-generation manufacturing and research environments.

This study applied the theory of comparative measurements to the assessment of surface topography parameters in accordance with ISO 5725:2019. The repeatability and reproducibility of the areal topography parameters  $S_a$ ,  $S_z$ , and  $S_q$  obtained using an atomic force microscope were analyzed on two reference standards and one sample.

The analysis of measurement series conducted over a four-year interval demonstrated a high degree of consistency in results. Differences in repeatability and reproducibility values before and after four years for two measurement series were below 1 nm, while for five series performed on Reference Standards 1 and 2, they remained below 2 nm for parameters  $S_a$  and  $S_q$ , and below 4 nm for  $S_z$ . The  $En$  agreement factor, remaining below 1, confirms the long-term stability of the measurement system. However, for the measurement sample, the  $En$  agreement factor close to 1 suggest that variations can be attributed to the non-uniformity of the sample surface.

Furthermore, the change of the measuring point on the reference standards did not significantly affect the results for  $S_a$  and  $S_q$ , while  $S_z$  exhibited notable dependence. The observed differences in measurements obtained with a time lag were attributed to random variability, reinforcing system stability. However, on the sample, the variation of the measuring point introduced reproducibility conditions, significantly influencing the measured areal topography parameters.

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