Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2026, 20(1), 406–422
https://doi.org/10.12913/22998624/210646
ISSN 2299-8624, License CC-BY 4.0

Received: 2025.07.03
Accepted: 2025.09.22
Published: 2025.11.21

Influence of digital optical microscope configuration and illumination conditions on the accuracy of surface roughness evaluation

Mateusz Rojewski[1]

[1] Faculty of Mechanical Engineering, Department of Manufacturing Techniques, Bydgoszcz University of Science and Technology, Kaliskiego 7, 85-796 Bydgoszcz, Poland
E-mail: mateusz.rojewski@pbs.edu.pl

ABSTRACT

Surface roughness is one of the key criteria for assessing surface condition across various industries. Even slight changes in topography can significantly affect the functional properties of components. Therefore, accurate roughness measurements require a comprehensive understanding of how measurement parameters influence the obtained results. This study analysed the impact of selected parameters of a digital optical microscope, as well as the characteristics of the light beam, on the accuracy of surface roughness reproduction compared to reference values. The investigation included the assessment of factors such as the direction of illumination, its intensity, depth composition step size, microscope magnification, and the resolution of the optical system. The main objective was to determine which of these parameters most significantly contribute to measurement distortions and to identify the optimal settings that enable reliable and repeatable measurements. The presented analyses may constitute a valuable contribution to the development of metrological procedures, improving the reliability of surface roughness measurements in both industrial and research practices. They also facilitate better adaptation of microscope settings to the specific features of the analysed surface, which is crucial for ensuring proper interpretation of results.

Keywords: digital microscopy, non-contact roughness measurement, linear roughness, microscope settings, light beam settings, Keyence.

INTRODUCTION

In modern industrial environments, the manufacturing and modification of components with stringent surface finish requirements has become a widespread practice. Enhancing mechanical properties [1], wear resistance [2], or providing protection against corrosion [3–5] are just a few examples of how surface performance and functionality can be improved. The resulting components require continuous quality control across a range of tribological parameters, necessitating the use of advanced measurement tools [6, 7]. The quality of a component's surface layer is one of the key indicators of its operational performance, directly affecting parameters such as friction, adhesion, and fatigue resistance [8]. Surface condition control is of critical importance in interacting machine components, parts in contact with liquids or gases, and medical implants [9–13]. In manufacturing engineering, surface roughness is considered one of the fundamental indicators of machining accuracy, assessed through a variety of metrological parameters. The most commonly used metrics are Ra (arithmetical mean deviation from the mean line) and Rz (mean peak to valley height) [14, 15]. Ra reflects the average deviation of the surface profile, while Rz represents the vertical distance between the highest peaks and the lowest valleys [16]. These parameters enable a precise assessment of surface quality and the standardisation of surface roughness specifications, which is essential for ensuring the desired functional properties of manufactured components [17, 18]. The increasing variety of available measurement techniques and the advancement of digital analytical methods allow for increasingly accurate and automated surface characterisation, supporting both process optimisation and quality assurance [19]. The most common classification of surface measurement methods includes contact [20, 21] and non-contact techniques [22, 23], each characterised by distinct operating principles and application scopes. Contact methods, such as mechanical profilometry, rely on a probe that physically interacts with the measured surface to register changes in profile height [24]. While offering high measurement accuracy, these methods also have notable limitations [25, 26]. A key drawback is the potential risk of damaging soft materials, protective coatings, or functional layers, for which mechanical contact may cause deformation or alteration of functional properties [27]. The analysis of complex geometries, especially curved surfaces, rough textures, or narrow features can be hindered by the physical limitations of the probe size and access [28–30]. Moreover, mechanical profilometers are highly sensitive to vibrations, which can distort measurement results, requiring operation in the environments with high mechanical stability and minimal external interference [31]. Another significant limitation of contact based techniques is their relatively low efficiency when analysing the surfaces with high topographic variability, steep inclines, or highly anisotropic structures. In such cases, errors may arise from the inability of the probe to accurately follow abrupt profile changes [32].

Due to these limitations, non-contact methods have gained considerable attention in recent years. These approaches eliminate the risk of surface damage and allow for faster, more comprehensive topographic analysis [33–35]. Commonly used techniques include interferometry, confocal microscopy, and 3D digital optical profilometry. These methods enable non-invasive imaging of surface microstructures with high precision, often down to the nanometer scale, making them particularly suitable for applications requiring detailed topographical evaluation of surface layers [36]. High resolution cameras and 3D reconstruction systems enable real time data acquisition, significantly improving measurement efficiency. The ability to archive results and perform subsequent analyses is especially beneficial in quality control, where long term monitoring of surface topography is crucial for evaluating process stability and identifying potential defects [37–39]. However, the accuracy of surface topography assessment using digital optical methods is influenced by numerous factors that may lead to distortion or deviations from actual values [40].

One of the most critical factors determining the accuracy of optical microscopy-based surface measurements is the lighting configuration. Parameters such as wavelength, type, and intensity of illumination significantly affect the fidelity of surface microstructure representation. Inappropriate lighting conditions, or the influence of external light sources, can result in artefacts such as shadows, reflections, or glare, distorting the true image of the sample and leading to incorrect measurement interpretations [41,42]. The nature of the examined surface is another important factor affecting imaging precision. Highly reflective materials such as polished metals, as well as transparent plastics, can interfere with image acquisition, making it difficult to obtain sharp focus. In such cases, optical filters, polarisation techniques, or lighting adjustments may be necessary to minimise undesirable effects. Measurement quality and accuracy are also affected by the optical resolution and quality of the microscope system itself. Insufficient resolution can lead to the loss of critical structural details, resulting in inaccurate surface topography reconstructions and errors in roughness parameter determination [43]. Additionally, as with contact methods, mechanical vibrations can adversely affect image quality. Even minor oscillations may blur structural details, impacting result repeatability and reliability. For surfaces with significant roughness, microscope magnification and the number of vertical scan layers become important factors. Inadequate layer coverage may result in incomplete surface representation, while poorly optimised image processing algorithms can lead to erroneous data interpretation [44–46].

The objective of this study was to identify and evaluate the microscope parameters most likely to introduce distortions in surface roughness measurements and to propose optimal settings that ensure accurate as well as repeatable results when using digital optical microscopy

MATERIALS AND METHODS

Surface roughness measurements were carried out using roughness reference specimens manufactured by LIMIT (Alingsås, Sweden). According to the manufacturer’s specification, the reference measurement plates were produced in compliance with ISO 2632/I-195 and made of non-alloy steel grade 1.0503, intended for heat treatment. The set of reference standards included surfaces obtained using six different machining methods (Figure 1).

For roughness measurements, surfaces produced by vertical milling were selected. The most commonly used surface texture parameter was measured, i.e., Ra – the arithmetic average deviation of the profile from the mean line. The Ra values for the examined reference surfaces, along with their respective designations and the applied cutoff filters λc and λs, are presented in Table 1. The selected cutoff filters were chosen in accordance with PN-ISO 4288.

Digital photographs of selected surface areas subjected to roughness analysis are presented in Figure 2. Surface roughness measurements using digital optical microscopy were carried out with a Keyence VHX-7000 microscope. The device was equipped with a VH-Z100R lens, allowing magnification from 100× to 1000×. For each analysed surface, 3D digital images were acquired to perform the roughness assessment. Imaging was conducted in multi-layer depth composition mode, which involves capturing a series of images at different focal planes, from the highest to the lowest point of the surface. The resulting images were then automatically combined into a single, fully focused image using the depth composition function. To eliminate variability due to operator influence, all measurements were performed by a single operator experienced in using digital microscopy and metrological data analysis. In order to minimise the impact of external factors, uniform and controlled measurement conditions were maintained: constant-intensity illumination, absence of daylight, and a stable ambient temperature of 21 °C. All measurements were conducted during a single measurement session, further reducing potential temporal variability.

The 3D digital microscope images used for surface roughness measurements were acquired using variable lighting parameters and adjustable functions of the optical microscope. The aspects analysed included: type and direction of illumination, light intensity, microscope magnification,

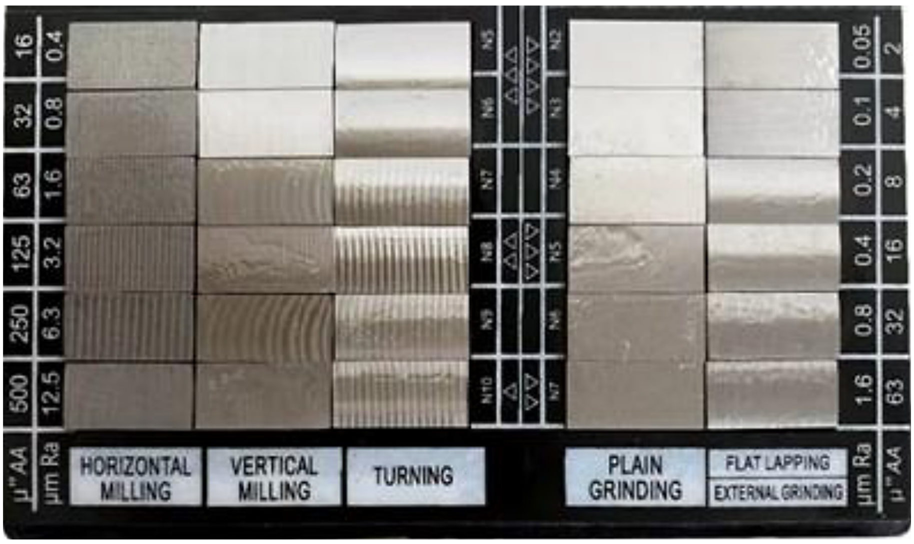

Figure 1. Surface roughness standards used for research

Table 1. Surface roughness values of the analysed samples along with their signatures and cutoff filters

Signature	Ra value [μm]	Reference length λc [mm]	Noise filter λs [μm]
S1	0.4	0.8	2.5
S2	0.8	0.8	2.5
S3	1.6	0.8	2.5
S4	3.2	2.5	8
S5	6.3	2.5	8
S6	12.5	8	25

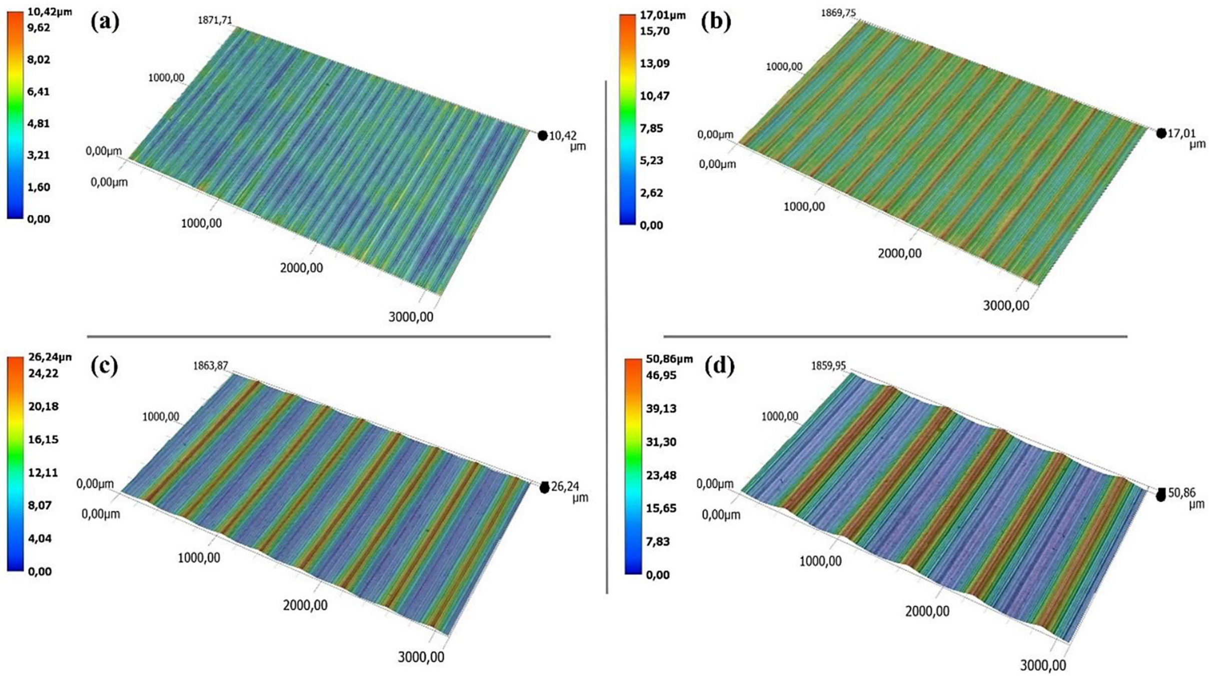

Figure 2. Representative 3D images of the analysed surfaces: (a) sample with surface roughness Ra = 0.8 μm, (b) Ra = 1.6 μm, (c) Ra = 6.3 μm, (d) Ra = 12.5 μm

digital resolution, and depth composition step size. The selection of these factors was based on the technical limitations of the measurement device, as well as practical application considerations related to measurement time, resolution, and the precision of surface topography reproduction.

The applied illumination modes: fully coaxial, fully ring-shaped, and mixed were selected to analyse the influence of light direction and incidence characteristics on the accuracy of surface roughness reproduction. The choice of these three modes was based on their widespread use in digital microscopy and the differing ways in which light interacts with the sample surface. Perpendicularly incident coaxial illumination is effective for analysing smooth, reflective surfaces by eliminating shadows and glare. Angled ring illumination better reveals three-dimensional structures, but may generate artefacts on glossy surfaces. The mixed mode combines the advantages of both methods, enabling the evaluation of trade-offs between contrast and geometric fidelity. All applied settings represent standard configurations available in the optical system of the employed microscope, which enhances the practical applicability of the results in industrial practice. A schematic diagram showing the illumination types, along with the corresponding 2D images of the examined surfaces, is presented in Figure 3.

Light intensities of 20 klx, 35 klx, and 50 klx were selected as the minimum, intermediate, and maximum adjustable values available in the Keyence VHX-7000 microscope. The selection of these levels aimed to assess how excessively low or high illumination intensity affects the accuracy of surface microstructure reproduction. Lower light intensities can help reduce overexposure and geometric distortions, particularly on highly reflective surfaces. In contrast, higher intensities enable better illumination of matte surfaces or those with significant height variations. The analysed intensity range covered typical operating conditions for microscopes used in industrial and research applications, while also allowing evaluation of this parameter across the full practical adjustment range of the device. Light intensity measurements were performed using a Sonel LXP-2 meter equipped with an LP-10B measurement probe.

In the case of the depth composition step size, the smallest applied value 1 μm was selected as the minimum adjustable setting available in the device, allowing for the highest possible resolution along the *Z*-axis. The remaining values (5 μm, 15 μm, 25 μm) were selected experimentally to ensure a representative distribution of parameter levels across the available scale. The

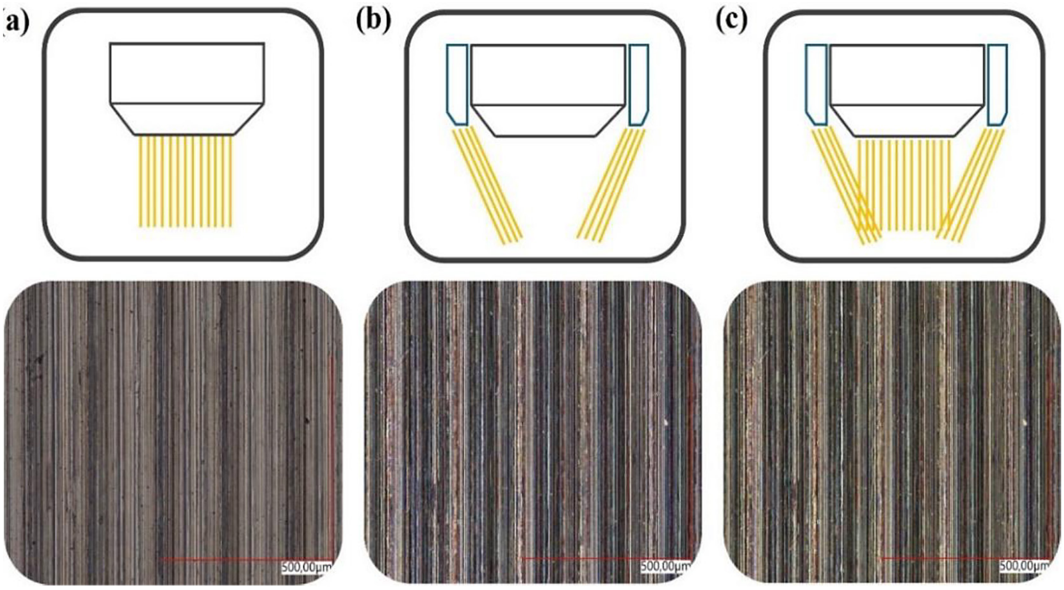

Figure 3. Schematic representation of the type and direction of illumination for the analysed surfaces: (a) fully coaxial light, (b) fully ring-shaped light, (c) mixed light

main objective was to determine whether, and to what extent, the depth composition step size influences the accuracy of surface roughness reproduction. Additionally, it should be noted that larger step sizes significantly reduce measurement time, which is particularly relevant in the industrial applications where time efficiency may be as important as measurement accuracy. The selected range of values enabled an evaluation of the trade-off between spatial resolution and measurement speed, which is of practical importance when selecting settings for different types of surfaces.

The magnification range was selected based on the optical capabilities of the VH-Z100R lens, which allows for continuous adjustment within the analysed interval. The use of 100× increments enabled a systematic assessment of the impact of resolution on the accuracy of roughness measurements. Lower magnifications (100×–300×), commonly used in industry for rapid inspection, may be insufficient for analysing microstructures. Higher magnifications (400×–1000×) can provide greater topographical detail but increase measurement time, which may be undesirable in high-throughput applications. For this reason, the full available magnification range was analysed to identify the optimal compromise between measurement accuracy and efficiency.

For each combination of microscope parameters, 10 independent measurements were performed, from which the arithmetic mean and standard deviation were calculated. These data served as the basis for assessing the internal repeatability of measurements under consistent experimental conditions. Additionally, to evaluate the influence of the analysed experimental factors on the obtained results, a one-way analysis of variance (ANOVA) was conducted. This allowed for statistical verification of whether the mean values in the tested groups differed significantly, with a significance level of $\alpha = 0.05$. Prior to conducting the main ANOVA, the assumptions required for its valid application were verified in each case. The normality of data distribution within groups was assessed using the Shapiro–Wilk test, while homogeneity of variances between groups was examined using Levene's test. In the cases where the ANOVA indicated statistical significance ($p < 0.05$), a post hoc analysis was performed using Tukey's HSD (Honestly Significant Difference) test to identify specific pairs of groups showing significant differences. Data analysis was carried out using Statistica 14 software (Dell Inc., United States). A summary of the factors used for roughness evaluation is presented in Table 2.

RESULTS

Type and direction of illumination

The first stage of the study involved verifying the effect of illumination direction on the accuracy of surface condition reproduction for the examined samples. The remaining parameters

Table 2. Adjustable parameters of the light beam and digital optical microscope applied in the study

Parameter	Value
Type of illumination	Fully coaxial Fully ring-shaped Mixed
Light intensity	20 klx 35 klx 50 klx
Depth composition step	1 μm 5 μm 15 μm 25 μm
Magnification	100x – 1000x

applied to acquire the 3D topography of the analysed surfaces were: 400× magnification, light intensity of 20 klx, and a depth composition step size of 5 μm. The analysis of this parameter was conducted on three types of surfaces: one with a reference roughness of Ra = 1.6 μm, another with Ra = 6.3 μm, and a third with Ra = 12.5 μm. On the basis of the obtained results (Table 3), it was found that the direction of illumination is a parameter that significantly affects the accuracy of roughness measurements.

The surface finish also plays an important role and should be taken into account when selecting the type of illumination. It was observed that the surfaces with relatively low roughness are more sensitive to changes in the direction of incident light. For the surface with a reference roughness of Ra = 1.6 μm, the highest level of agreement with the reference standard was achieved using coaxial illumination, where the deviation from the reference value was only 1.31%. In contrast, ring and mixed illumination resulted in significantly higher deviations of 26.31% and 23.8%, respectively. This phenomenon can be explained by the manner in which light propagates. Under ring and mixed illumination, light strikes the surface at an angle and is scattered in various directions. As a result, some surface areas may become shadowed, while others are more intensely illuminated. Increased contrast at microstructural boundaries can lead to interpretation errors. For the surfaces with relatively low roughness (Ra = 1.6 μm), even minor irregularities may generate strong local contrasts, which the analysis system interprets as more pronounced and deeper structures. This leads to an overestimation of roughness values. In the case of surfaces with higher roughness (Ra = 6.3 μm), the results obtained for different illumination types were close to the reference values, suggesting that under such conditions, the type of illumination has a smaller impact on the accuracy of surface topography reproduction. For this structure, similar Ra values were recorded regardless of the illumination mode. The underestimation of Ra compared to the reference ranged from approximately 4% (ring illumination) to about 6% (mixed illumination). For the surfaces with high roughness (Ra = 12.5 μm), deviations from the reference were even smaller, ranging from 0% to 2.32% across all analysed illumination modes. The improvement in surface reproduction accuracy with increasing roughness is again related to how light interacts with the illuminated surface. At higher Ra values, the surface contains larger and more distinct irregularities, which scatter light in multiple directions regardless of the angle of incidence. As a result, both angled ring illumination and perpendicular coaxial illumination are scattered to a similar degree, minimising the influence of illumination direction on the measurement results.

Table 3. Effect of illumination direction on the accuracy of surface roughness reproduction for the reference standard

Type of surface	Type of illumination	Ra result, μm	Dimensional deviation from reference, %
S3 Ra = 1.6 μm	Fully coaxial	1.62 ± 0.02	+ 1.31
	Fully ring shaped	2.02 ± 0.06	+ 26.31
	Mixed	1.98 ± 0.01	+ 23.8
S6 Ra = 6.3 μm	Fully coaxial	5.98 ± 0.03	- 5.08
	Fully ring shaped	6.04 ± 0.07	- 4.13
	Mixed	5.93 ± 0.07	- 5.87
S6 Ra = 12.5 μm	Fully coaxial	12.50 ± 0.06	+ 0
	Fully ring shaped	12.57 ± 0.03	+ 0.56
	Mixed	12.79 ± 0.05	+ 2.32

Similar results were reported by Grochalski et al. [47], who found that the direction of light incidence on the examined surface in optical profilometry affects the accuracy of surface topography measurements. Accurate roughness results were observed when using coaxial illumination (directly through the objective lens) or uniform ring illumination with all sectors of the light source around the ring activated. Elango et al. [48] demonstrated that lighting conditions, such as the angle of incidence, distance from the light source, and the orientation of the surface structure relative to the illumination direction have a significant impact on roughness evaluation results in vision systems. Their study showed that the angle of light incidence, in particular, had a pronounced effect on image-derived parameters, emphasising the importance of carefully selecting lighting conditions for optical measurements.

Table 4 presents the results of a one-way analysis of variance (ANOVA) conducted to evaluate the statistical significance of the effect of illumination type on the measured surface parameter.

For the reference surfaces with Ra = 1.6 μm and 12.5 μm, the ANOVA results indicated statistically significant differences between groups, confirming that the type of illumination significantly affects the accuracy of surface roughness reproduction for these structures. In contrast, no statistically significant differences were found for Ra = 6.3 μm. Although the Ra values for 12.5 μm were close to the nominal reference, ANOVA identified significant differences between illumination types, as it evaluates differences between group means, rather than agreement with reference values. In this case, mean values for each illumination mode differed with low within-group variability, while for Ra = 6.3 μm the between-group differences were smaller than the internal dispersion, preventing statistical significance. Tukey's test results for surfaces with significant differences are presented in Table 5.

For the surface with a reference roughness of Ra = 1.6 μm, both coaxial and ring illumination differed significantly from mixed illumination, confirming the influence of illumination type on measurement results. However, the difference between ring and mixed illumination was not statistically significant, indicating that these two modes yield similar outcomes. For the surface with Ra = 12.5 μm, significant differences were observed between coaxial and mixed illumination, as well as between mixed and ring illumination. No significant difference was found between coaxial and ring illumination, indicating that at this roughness level, mixed illumination deviates the most from the other two variants.

Light intensity

The next stage of the study involved analysing the effect of microscope light intensity on the accuracy of surface roughness reproduction. As in the evaluation of illumination direction, three surfaces with Ra values of 1.6 μm, 6.3 μm, and 12.5 μm were selected. On the basis of previous

Table 4. Results of one-way analysis of variance (ANOVA) for surface roughness measurements depending on the type of illumination used. P-values < 0.05 were considered statistically significant and are marked with an asterisk (*)

Type of surface	F-value	p-value	Statistical significance
S3 Ra = 1.6 μm	120.54	< 0.001*	Significant effect
S6 Ra = 6.3 μm	3.57	0.06	No significance
S6 Ra = 12.5μm	55.21	< 0.001*	Significant effect

Table 5. Results of Tukey's HSD post hoc tests for different pairs of illumination types. P-values < 0.05 were considered statistically significant and are marked with an asterisk (*)

Type of surface	Group I	Group II	p-value	Statistical significance
Ra = 1.6 μm	Fully coaxial	Mixed	< 0.001*	Significant effect
	Fully coaxial	Ring-shaped	< 0.001*	Significant effect
	Mixed	Ring-shaped	0.304	No significance
Ra = 12.5 μm	Fully coaxial	Mixed	< 0.001*	Significant effect
	Fully coaxial	Ring-shaped	0.515	No significance
	Mixed	Ring-shaped	< 0.001*	Significant effect

results, fully coaxial illumination was used for further analysis. The microscope magnification was set to 400×, and the depth composition step size was 5 µm. The measurement results are summarised in Table 6.

On the basis of the presented results, it was found that light intensity affects the accuracy of roughness profile reproduction, although to a lesser extent than illumination direction. A general trend was observed, indicating that measurements taken at the lowest analysed intensity (20 klx) showed the smallest deviations from the reference values. For example, for the surface with Ra = 1.6 µm, the measured value at the lowest light intensity was 1.59 µm. As the light intensity increased, the deviation from the reference value slightly increased, although the differences remained small and often fell within the standard deviation range of previous readings. For the same surface, the measurement at the highest intensity (50 klx) yielded an Ra value of 1.52 µm, representing a decrease of approximately 5% compared to the reference.

The higher agreement with the reference standard observed at lower light intensity (20 klx) is likely due to the reduction of optical artefacts that become more pronounced at higher illumination levels. First, excessive light intensity can lead to overexposure in parts of the microscope image, resulting in the loss of local contrast between surface microfeatures. On smooth surfaces, this may cause excessive blurring of microstructure edges and loss of contrast. Additionally, the metallic nature of the tested samples makes them particularly susceptible to overexposure and strong reflections under high-intensity lighting. At elevated intensities, the sensor of the microscope camera may also become saturated, reducing its ability to capture subtle height differences between microelements on the surface. As a result of these phenomena, measurements taken at maximum illumination levels tend to underestimate surface roughness values. Especially in the case of smooth surfaces, where high sensitivity and precision in microstructure reproduction are essential. In addition to illumination direction and intensity, other factors also affect surface reproduction accuracy. Ružbarský [49] showed that laser light wavelength significantly influences the accuracy of non-contact roughness measurements on AISI 304 stainless steel. The smallest deviations from contact measurements occurred at 445 nm, while longer wavelengths produced overestimated results. Strong reflections from smooth, glossy surfaces can distort measurements, limiting the use of laser profilometry in such cases.

Statistical analysis using ANOVA demonstrated a statistically significant effect of light intensity on the accuracy of surface roughness reproduction across all analysed illumination levels (Table 7). This result clearly confirms that variations in illumination intensity influence the roughness measurement outcome, regardless of the reference Ra value of the examined surface.

Post hoc testing revealed that for the surface with Ra = 1.6 µm, a statistically significant difference occurred between the 20 klx and 50 klx light intensities (Table 8). For the Ra = 6.3 µm surface, significant differences were found between 20 klx and 50 klx, as well as between 35 klx and 50 klx. Similarly, for Ra = 12.5 µm, statistically significant differences were observed between both 20 klx and 50 klx, and 35 klx and 50 klx. These results clearly confirm that increased light intensity may lead to undesirable alterations in surface topography reproduction, particularly for

Table 6. Effect of illumination intensity on the accuracy of surface roughness reproduction for the reference standard

Type of surface	Light intensity	Ra result, µm	Dimensional deviation from reference, %
S3 Ra = 1.6 µm	Min value – 20 klx	1.59 ± 0.04	- 0.62
	Middle value – 35 klx	1.54 ± 0.02	- 3.75
	Max value – 50 klx	1.52 ± 0.04	- 4.75
S6 Ra = 6.3 µm	Min value – 20 klx	5.95 ± 0.02	- 5.95
	Middle value – 35 klx	5.89 ± 0.04	- 6.51
	Max value – 50 klx	5.86 ± 0.04	- 6.98
S6 Ra = 12.5 µm	Min value – 20 klx	12.52 ± 0.03	+ 0.16
	Middle value – 35 klx	12.51 ± 0.02	+ 0.08
	Max value – 50 klx	12.43 ± 0.04	- 0.53

Table 7. Results of one-way analysis of variance (ANOVA) for surface roughness measurements depending on the applied illumination intensity. P-values < 0.05 were considered statistically significant and are marked with an asterisk (*)

Type of surface	F-value	p-value	Statistical significance
S3 Ra = 1.6 μm	5.31	0.02*	Significant effect
S6 Ra = 6.3 μm	11.42	0.0017*	Significant effect
S6 Ra = 12.5μm	13.01	< 0.001*	Significant effect

Table 8. Results of Tukey's HSD post hoc tests for different pairs of illumination intensity levels. P-values < 0.05 were considered statistically significant and are marked with an asterisk (*)

Type of surface	Group I	Group II	p-value	Statistical significance
Ra = 1.6 μm	20 klx	35 klx	0.11	No significance
	20 klx	50 klx	0.02*	Significant effect
	35 klx	50 klx	0.59	No significance
Ra = 6.3 μm	20 klx	35 klx	0.02*	Significant effect
	20 klx	50 klx	0.001*	Significant effect
	35 klx	50 klx	0.31	No significance
Ra = 12.5 μm	20 klx	35 klx	0.78	No significance
	20 klx	50 klx	0.001*	Significant effect
	35 klx	50 klx	0.004*	Significant effect

samples with higher roughness. Therefore, selecting an appropriate illumination level during the measurement process is crucial to ensure result reliability and repeatability.

Depth composition step

The next analysed parameter was the depth composition step size, which defines the distance between successive focal planes during the acquisition of the 3D surface topography image. Measurements were performed using fully coaxial illumination at an intensity of 25 klx and a microscope magnification of 400×. The results of surface roughness reproduction accuracy for the reference standard are summarized in Table 9.

The obtained results demonstrated that the depth composition step size affects the accuracy of surface roughness measurements. This parameter proved to be particularly important when

Table 9. Effect of depth composition step size on the accuracy of surface roughness reproduction for the reference standard

Type of surface	Depth composition step, μm	Ra result, μm	Dimensional deviation from reference, %
S3 Ra = 1.6 μm	1	1.66 ± 0.03	+ 3.75
	5	1.65 ± 0.01	+ 3.00
	15	1.71 ± 0.20	+ 7.13
	25	2.36 ± 0.35	+ 47.75
S6 Ra = 6.3 μm	1	5.89 ± 0.06	- 6.46
	5	5.93 ± 0.06	- 5.87
	15	5.95 ± 0.07	- 5.56
	25	6.81 ± 0.23	+ 8.10
S6 Ra = 12.5 μm	1	12.39 ± 0.06	- 0.88
	5	12.43 ± 0.07	- 0.54
	15	12.76 ± 0.07	+ 2.05
	25	13.06 ± 0.75	+ 4.45

analysing highly finished surfaces. For example, for the reference sample with Ra = 1.6 μm, using a small step size of 1 μm or 5 μm resulted in values closest to the reference. The deviation for a 1 μm step was 3.75%, while for 5 μm it was 3.00%. Increasing the step size to 25 μm resulted in a roughness value differing from the reference by as much as 47.75%. Such a significant overestimation confirms that, for low-roughness surfaces, a larger step causes a serious loss of measurement accuracy. For the reference surfaces with Ra = 6.3 μm and Ra = 12.5 μm, the influence of depth composition step size on the measurement result was also observed, although it was less pronounced. A general trend was also noted: an excessively large step tends to overestimate surface topography, while an overly small step tends to underestimate it. These results indicate that for high-roughness surfaces (Ra = 12.5 μm), the digital system is less sensitive to the changes in the depth composition step parameter, whereas for medium-roughness surfaces (Ra = 6.3 μm), increasing the step size may noticeably reduce measurement accuracy.

The decrease in surface topography reproduction accuracy with increasing depth composition step size is most likely due to the reduced number of focal planes captured by the optical system of the microscope. With a larger step, fewer layers along the Z-axis are analysed, which may lead to the omission of fine topographical details, particularly in the case of surfaces with low or medium roughness. As a result, the surface may be incompletely or inaccurately represented, leading to erroneous determination of roughness parameters. Additionally, interpolation algorithms used in the measurement system may, at large intervals between focal layers, introduce the distortions that result in artificial smoothing or overestimation of the surface structure. For surfaces with higher roughness, the effect of step size is less significant, as the height differences are pronounced enough to allow accurate geometric reproduction even with less frequent sampling.

According to the results of the analysis of variance (ANOVA), a statistically significant effect of the depth composition step size on the accuracy of Ra parameter measurement was demonstrated for each of the analysed surfaces (Table 10). For the reference surface with Ra = 12.5 μm, the p-value was at the threshold of statistical significance, confirming the reduced sensitivity of the optical system to changes in step size for surfaces with low surface finish. A particularly pronounced effect was observed for the surface with Ra = 1.6 μm, which may indicate a high sensitivity of such structures to Z-axis resolution during measurement.

On the basis of the results of Tukey's post hoc tests, statistically significant differences between pairs of depth composition step sizes were found only for the reference surfaces with Ra = 1.6 μm and Ra = 6.3 μm. The results for these surfaces are presented in Table 11. For the surface with Ra = 12.5 μm, no significant differences were observed between the analysed pairs, confirming that the surfaces with a low degree of finish are less sensitive to changes in the analysed parameter. For the pairs where statistical significance was found, no notable differences were observed between step sizes ranging from 1 μm to 15 μm. Thus, it can be concluded that in the studies of surfaces with low and medium roughness, the use of very small depth composition steps is not necessary, as they do not significantly affect the measurement result.

Microscope magnification and resolution

The final stage of the study involved analysing the effect of microscope magnification on the accuracy of roughness measurements relative to reference values. On the basis of previous findings, fully coaxial illumination was used with a light intensity of 25 klx and a depth composition step size of 5 μm. To verify the influence of specific magnification levels on measurement results for surfaces with varying roughness, each reference plate produced by vertical milling was analysed individually. Five magnification levels were used

Table 10. Results of one-way analysis of variance (ANOVA) for surface roughness measurements depending on the applied depth composition step size. P-values < 0.05 were considered statistically significant and are marked with an asterisk (*)

Type of Surface	F-value	p-value	Statistical significance
S3 Ra = 1.6 μm	62.83	< 0.001*	Significant effect
S6 Ra = 6.3 μm	14.52	< 0.001*	Significant effect
S6 Ra = 12.5 μm	3.402	0.04*	Significant effect

Table 11. Results of Tukey's HSD post hoc tests for different pairs of applied depth composition step sizes. P-values < 0.05 were considered statistically significant and are marked with an asterisk (*)

Type of Surface	Group I	Group II	p-value, Ra = 1.6 μm	p-value, Ra = 6.3 μm	Statistical significance
Ra = 1.6 μm and Ra = 6.3 μm	1 μm	5 μm	0.99	0.95	No significance
	1 μm	15 μm	0.06	0.89	No significance
	1 μm	25 μm	< 0.001*	< 0.001*	Significant effect
	15 μm	5 μm	0.95	0.99	No significance
	15 μm	25 μm	< 0.001*	< 0.001*	Significant effect
	25 μm	5 μm	< 0.001*	< 0.001*	Significant effect

Table 12. Results of the experimental series showing the effect of magnification on the accuracy of roughness measurement

Type of surface	Magnification	Ra result, μm	Dimensional deviation from reference, %
S1 Ra = 0.4 μm	100x	1.33 ± 0.06	+ 232.5
	200x	1.03 ± 0.06	+ 157.5
	300x	1.01 ± 0.04	+ 152.5
	400x	0.91 ± 0.06	+ 127.5
	500x	0.77 ± 0.03	+ 92.5
S2 Ra = 0.8 μm	100x	1.09 ± 0.08	+ 36.25
	200x	0.91 ± 0.02	+ 13.75
	300x	0.86 ± 0.02	+ 7.51
	400x	0.83 ± 0.02	+ 3.75
	500x	0.78 ± 0.02	- 2.50
S3 Ra = 1.6 μm	100x	1.82 ± 0.04	+ 13.75
	200x	1.74 ± 0.03	+ 8.75
	300x	1.63 ± 0.02	+ 1.88
	400x	1.62 ± 0.03	+ 1.25
	500x	1.59 ± 0.08	- 0.63
S4 Ra = 3.2 μm	100x	2.52 ± 0.48	- 21.25
	200x	2.75 ± 0.03	- 14.06
	300x	2.89 ± 0.01	- 9.69
	400x	2.91 ± 0.07	- 9.06
	500x	3.22 ± 0.11	+ 0.63
S5 Ra = 6.3 μm	100x	5.33 ± 0.21	- 15.39
	200x	5.45 ± 0.02	- 13.49
	300x	5.57 ± 0.04	- 11.58
	400x	5.92 ± 0.01	- 6.03
	500x	6.14 ± 0.05	- 2.54
S6 Ra = 12.5 μm	100x	11.35 ± 0.26	- 9.21
	200x	12.18 ± 0.06	- 2.26
	300x	12.41 ± 0.05	- 0.81
	400x	12.58 ± 0.09	+ 0.64
	500x	12.61 ± 0.07	+ 0.88

in the study: 100×, 200×, 300×, 400×, and 500×. The measurement results are presented in Table 12.

The obtained results demonstrated that microscope magnification plays a critical role in the accuracy of surface topography reproduction. In all experimental series, the use of the lowest magnification (100×) resulted in the greatest deviations from reference values. As the magnification gradually increased, the measured results became closer to the reference values, with the best agreement typically achieved at 500×. However, this trend was observed in all series except for series S1 (Ra = 0.4 μm), where the measurement results significantly deviated from the reference values regardless of the magnification used. In this case, even the highest magnification led to an overestimation of nearly 100% (Ra = 0.77 μm). For the surface with Ra = 0.8 μm (S2), a clear improvement in accuracy with increasing magnification was also observed. From +36.25% at 100× to −2.5% at 500×. For the surfaces with reference roughness in the range from S3 (Ra = 1.6 μm) to S5 (Ra = 6.3 μm), the measurements were less sensitive to magnification changes. However, using 100× and 200× magnifications often resulted in deviations from the reference values. For example, for sample S3, a measurement at 100× yielded Ra = 1.82 μm (+13.75%), while at 400× it was 1.62 μm (+1.25%). In the case of S4 (Ra = 3.2 μm), the result at 100× was 2.52 μm, indicating an underestimation of 21.25%, while at 500× it was 3.22 μm (+0.63%). However, the effect of magnification on measurement accuracy in these cases was not as pronounced as in the previously mentioned low-roughness surfaces (e.g., Ra = 0.4 μm, where the measurement error at 100× reached +235.5%). For the surface with the highest roughness (S6, Ra = 12.5 μm), the impact of magnification was marginal. Only at 100× was a relatively high deviation of −9.21% observed. The difference between the results at 200× and 500× was minimal. This measurement stability suggests that the microstructure of highly rough surfaces is pronounced enough to be accurately captured even at lower magnification levels.

Using higher magnifications in digital optical microscopy can result in the roughness values that are closer to the reference values for several important reasons. Higher magnifications provide greater resolution, allowing the microscope to capture finer details of the surface topography, such as micro-irregularities, grooves, and peaks that may be missed at lower magnifications. In addition, higher magnifications reduce the influence of optical effects such as edge blurring or spherical aberrations, which at low magnifications can lead to artificial image smoothing or incorrect reproduction of microstructures. Higher magnifications also allow for more accurate separation of adjacent surface features, reducing the risk of their overlapping and misestimation of roughness parameters. Moreover, at higher magnification, the microscope performs more precise sampling of surface height variations, enabling accurate detection of even minor changes in microstructure. As a result, these factors contribute to measurements taken at higher magnifications being more consistent with the actual surface characteristics, making them more reliable and representative in the context of surface roughness evaluation using digital optical microscopy. It should be noted, however, that using such magnification levels with samples of higher roughness, which require sufficiently long measurement lengths for accurate assessment, leads to a significant increase in measurement time, which may extend to several minutes.

On the basis of the ANOVA statistical analysis, statistically significant differences between magnification groups were found for all examined reference Ra levels. The obtained results clearly confirm that the selection of magnification level is a key factor influencing the accuracy of roughness reproduction in optical microscopy, regardless of the surface finish of the analysed sample (Table 13).

Surface roughness measurement of highly polished surfaces (Ra = 0.4 μm) using the applied microscope settings proved to be challenging and, in some cases, impossible to perform with the required accuracy. Therefore, an additional analysis was conducted to verify whether, for low-roughness surfaces, the use of higher magnification levels from 600× to 1000× is justified. The results are presented in Table 14. The use of high magnifications did not improve the accuracy of surface topography reproduction. The obtained Ra values were slightly lower than those measured at previously analysed magnifications in the 100×–500× range. Each measurement showed surface roughness values nearly twice as high as the reference. Additionally, due to the relatively short evaluation length for this level of roughness (4.8 mm), the measurement time increased significantly. For example, at 800× magnification, the measurement took 5 minutes and 36 seconds, while at 1000× it lasted 8 minutes and 53 seconds.

The observed deviations were most likely caused by the limited resolution of the digital microscope used in the study. This limitation was particularly significant along the Z-axis, which is responsible for accurately reproducing height differences in microstructures. For surfaces with Ra = 0.4 μm, the topographical irregularities are small, often within tenths of a micrometre. Such values may fall below the detection threshold of the measurement system. As a result, even when

Table 13. Results of one-way analysis of variance (ANOVA) for surface roughness measurements depending on the applied magnification. P-values < 0.05 were considered statistically significant and are marked with an asterisk (*)

Type of surface	F-value	p-value	Statistical significance
S1 Ra = 0.4 µm	24.13	< 0.001*	Significant effect
S2 Ra = 0.8 µm	12.32	< 0.001*	Significant effect
S3 Ra = 1.6 µm	9.48	< 0.001*	Significant effect
S4 Ra = 3.2 µm	12.78	< 0.001*	Significant effect
S4 Ra = 6.3 µm	36.51	< 0.001*	Significant effect
S6 Ra = 12.5 µm	39.41	< 0.001*	Significant effect

Table 14. Effect of high magnifications on the accuracy of roughness measurement for highly polished surfaces

Type of surface	Magnification	Ra result, µm	Dimensional deviation from reference, %
S1 Ra = 0.4 µm	600x	0.75 ± 0.02	- 87.5
	700x	0.69 ± 0.03	- 72.5
	800x	0.72 ± 0.02	- 80
	900x	0.70 ± 0.01	- 75
	1000x	0.76 ± 0.03	- 90

using high magnifications, minor height differences may not be sufficiently pronounced to be accurately registered by the optical system. Furthermore, microscopes employing depth composition techniques require clearly distinguishable differences in focus between successive optical layers. For very smooth surfaces, characteristic focal points are often absent, leading to incomplete or incorrect 3D topography reconstruction. Additional difficulties may arise from local light reflections, which are typical of highly reflective surfaces and can cause image distortion as well as loss of structural information. Consequently, despite the use of higher magnification, no improvement in measurement accuracy was observed, and the obtained Ra values significantly deviated from the reference. Rosentritt et al. [50] demonstrated that, in confocal microscopy, magnification also has a significant effect on the values of measured surface roughness parameters. In their study, it was observed that increasing magnification—from 5× to 50×—led to a clear decrease in the measured parameter values. The highest roughness values were recorded at the lowest magnification (5×), while the lowest values were obtained at the highest magnification (50×). These results indicate that magnification influences not only the level of image detail but also the range of detected surface irregularities, which can lead to considerable differences in the assessment of the same topography of the surface. The authors emphasize that the lack of standardisation in magnification settings can significantly compromise the comparability of results between different studies.

Due to the lack of agreement between the measured roughness values of the highly polished surface (Ra = 0.4 µm) and the reference values, an analysis was conducted to evaluate the effect of optical microscope resolution on topography reproduction accuracy. For this purpose, a modern digital microscope model – Keyence VHX-X1 with the FI HEAD measurement unit was used. Since accurate results had already been obtained for the surfaces with roughness exceeding Ra = 0.8 µm, measurements were performed exclusively for the S1 sample, using selected magnification levels. Spatial resolution, expressed in micrometres per pixel (µm/pixel), depends on both the magnification level and the type of microscope used. These values are presented in Table 15 for both measurement systems. This parameter defines the actual surface area represented by a single image pixel. A lower value indicates a higher pixel density per unit area, which translates into greater image detail and higher spatial resolution of the system. The obtained comparison indicates that the VHX-X1 microscope offers higher resolution capability at the same magnification levels.

On the basis of the data presented in Table 15, it was found that the resolution of a digital microscope has a significant impact on the accuracy of surface roughness reproduction for highly

Table 15. Comparison of optical microscope resolutions and the corresponding Ra roughness values obtained

Magnification	Resolution of Keyence VHX – X1	Ra result, μm	Dimensional change,%	Resolution of Keyence VHX – 7000	Ra result, μm	Dimensional change, %
500x	0.2 μm/pixel	0.60 ± 0.02	50	0.29 μm/pixel	0.92 ± 0.03	130
700x	0.15 μm/pixel	0.61 ± 0.01	52.5	0.21 μm/pixel	0.69 ± 0.03	72.5
1000x	0.1 μm/pixel	0.42 ± 0.03	5	0.15 μm/pixel	0.76 ± 0.03	90

Table 16. Potential sources of errors and their impact on surface roughness measurement results

Source of error	Description of influence mechanism	Recommendations	Remarks
Type of illumination	Shadows, reflections, and overexposure can distort topography reconstruction.	Using coaxial illumination.	Particularly important for highly finished surfaces.
Light intensity	Excessive intensity causes overexposure, sensor saturation, and loss of contrast; insufficient intensity leads to underexposure of details.	Using lower intensity ranges (e.g., 20–25 klx).	Greater impact on metallic and glossy surfaces.
Depth composition step	A step that is too large omits fine details in the Z-axis; too small increases measurement time.	Using a smaller step for low-roughness surfaces; for highly rough surfaces, a larger step can be used to shorten measurement time.	The effect of the depth composition step decreases as roughness increases.
Microscope magnification	Too low magnification limits spatial resolution and causes loss of detail; too high may extend measurement time without improving accuracy.	Using magnification ≥ 400×.	Very smooth surfaces (Ra < 1 µm) are difficult to measure even at high magnifications.
Optical system resolution	Limited resolution (µm/pixel) may prevent detection of very small height differences.	Using equipment with high spatial resolution.	Differences of around 0.09 µm/pixel significantly improve results.
Material reflectivity	Metallic and polished surfaces cause reflections and focus disturbances.	Using appropriate lighting and reduce light intensity.	May require individual settings for each material.
Vibrations and workstation instability	Vibrations cause image blurring, loss of detail, and reduced measurement repeatability.	Performing measurements on a stable anti-vibration table; avoiding working near vibration sources.	Applies to all optical methods, especially at high magnifications.
Environmental conditions (temperature, external light)	Temperature changes can cause thermal expansion of samples; external light affects optical measurements.	Maintaining constant temperature (e.g., 21°C) and eliminating daylight exposure.	Stable conditions eliminate environmental influence on results.
Operator differences	Subjective parameter selection can cause result variability.	Performing all measurements by one experienced operator or follow a strictly defined procedure.	A uniform procedure reduces measurement variability.

polished samples. A comparison of the two microscope models showed that the newer system offers higher accuracy in surface topography reproduction. For all analysed magnification levels (500×, 700×, 1000×), the VHX-X1 microscope recorded roughness values much closer to the reference values compared to the VHX-7000. For example, at 1000× magnification using the VHX-X1, a value of Ra = 0.42 ± 0.03 µm (5% error) was obtained, while the VHX-7000 recorded Ra = 0.76 ± 0.03 µm, corresponding to an error of approximately 90%. A similar trend was observed at 500× and 700× in each case, the VHX-X1 enabled more accurate surface topography reproduction. Even a relatively small difference in spatial resolution. For instance, 0.2 µm/pixel compared to 0.29 µm/pixel resulted in a noticeable improvement in measurement quality and precision. These findings clearly indicate that accurate reproduction of low-roughness surfaces requires optical systems with high resolution. More advanced measurement systems, such as the one used in the VHX-X1 microscope, allow for more effective detection of small height differences in microstructures, resulting in increased reliability of the measurement results.

On the basis of the conducted research, a summary table was developed listing potential sources of error that may occur during surface roughness measurements using digital optical microscopy. Table 16 includes the factors related to microscope settings and the measurement environment, as well as those arising from sample preparation and operator actions. For each factor, the mechanism of its influence on the result, the estimated range of possible distortion in the Ra value, and practical recommendations for minimising its effect are provided. Such a compilation can serve as a useful reference point when planning and performing measurements in both laboratory and industrial settings, helping to minimise the risk of metrological error.

CONCLUSIONS

This article presented the research results concerning the influence of digital optical microscope parameters and light beam settings on the accuracy of surface roughness reproduction with respect to reference surfaces. Surface roughness measurements, a key element of surface quality assessment across many industrial sectors, require precise tools and analytical methods to ensure reliable outcomes. The study focused on evaluating the influence of parameters, such as light incidence direction, beam intensity, microscope magnification, resolution, and depth composition step size. The results demonstrated that accurate surface roughness measurements require comprehensive synchronisation of these parameters.

It was found that microscope magnification and light incidence direction have the greatest impact on measurement accuracy. As magnification increased, roughness measurement results became more consistent with reference values. It was shown that at 500× magnification, deviations from reference values did not exceed 3%. It is worth noting that the measurement system used in this study encountered difficulties in measuring highly polished surfaces (Ra = 0.4 μm), which was attributed to insufficient microscope resolution. On the basis of the results, it can be concluded that the selection of appropriate magnification should consider both the resolving power of the microscope and the characteristics of the examined surface. For the samples with smooth, highly finished surfaces, high resolution and magnification are essential to obtain reliable surface condition data.

The study also demonstrated that roughness measurements using digital optical microscopy should be conducted with full coaxial lighting directed perpendicularly to the surface. Regarding beam intensity, measurements performed with lower light intensity proved more effective than those conducted under higher intensity. The optimal depth composition step should range from 5 μm to 10 μm. However, for highly polished surfaces, lower step sizes should be applied. It must also be noted that increasing the depth composition step significantly prolongs the measurement time.

The presented data confirm that optimisation of microscope parameters combined with appropriate light settings is crucial for accurate roughness measurement. This is of particular importance in industrial and research applications such as quality control or the analysis of tribological properties of engineering materials. The results can support the optimisation of metrological procedures and contribute to the development of measurement standards for digital surface analysis. For future research, it is advisable to conduct comparative studies involving digital optical microscopes of varying resolutions, as well as to extend the analysis to include advanced lighting technologies or comparisons between optical microscopy and other techniques such as interferometry and scanning electron microscopy.

REFERENCES

1. Bonu, V.; Barshilia, H.C. High-temperature solid particle erosion of aerospace components: its mitigation using advanced nanostructured coating technologies. Coatings 2022, 12, 1979.
2. Wasekar, N.P.; Bathini, L.; Ramakrishna, L.; Rao, D.S.; Padmanabham, G. Pulsed electrodeposition, mechanical properties and wear mechanism in Ni-W/SiC nanocomposite coatings used for automotive applications. Appl. Surf. Sci. 2020, 527, 146896.
3. Huang, N.; Wang, Y.; Zhang, Y.; Liu, L.; Yuan, N.; Ding, J. Multifunctional coating on magnesium alloy: Superhydrophobic, self-healing, anti-corrosion and wear-resistant. Surf. Coat. Technol. 2023, 463, 129539.
4. Nazarzade, K.; Naderi, R.; Mahdavian, M. Fabrication of corrosion-resistant conversion coating based on ZIF-8 on electrogalvanized steel utilizing pulse electrodeposition technique. Surf. Coat. Technol. 2023, 457, 129292.
5. Zhang, S.N.; Chen, Z.; Arfaei, B. Graphene coating as a corrosion protection barrier for metallic terminals in automotive environments. SAE Int. J. Adv. Curr. Pract. Mobil. 2021, 3, 3176–3183.
6. Ramezani, M.; Pasang, T.; Chen, Z.; Neitzert, T.; Au, D. Evaluation of carbon diffusion in heat treatment of H13 tool steel under different atmospheric conditions. J. Mater. Res. Technol. 2015, 4, 114–125.
7. Li, H.; Ramezani, M.; Chen, Z.; Singamneni, S. Effects

of process parameters on temperature and stress distributions during selective laser melting of Ti–6Al–4V. Trans. Indian Inst. Met. 2019, 72, 3201–3214.

8. Tevis, D.; Jacobs, B.; et al. Surf. Topogr.: Metrol. Prop. 2017, 5, 013001 https://doi.org/10.1088/2051-672X/aa51f8
9. Pastewka, L.; Robbins, M.O. Contact between rough surfaces and a criterion for macroscopic adhesion. Proc Natl Acad Sci U S A. 2014 Mar 4, 111(9), 3298–303. https://doi.org/10.1073/pnas.1320846111
10. Müser, M.H. A dimensionless measure for adhesion and effects of the range of adhesion in contacts of nominally flat surfaces, Tribology International, 2016, 100, 41–47, https://doi.org/10.1016/j.triboint.2015.11.010
11. Wang, B.; Meng, X.; Peng, X.; Chen, Y. Experimental investigations on the effect of rod surface roughness on lubrication characteristics of a hydraulic O-ring seal. Tribol. Int. 2021, 156, 106791.
12. Romero, M.; Herrero-Climent, M.; Ríos-Carrasco, B.; Brizuela, A.; Romero, M.M.; Gil, J. Investigation of the influence of roughness and dental implant design on primary stability via analysis of insertion torque and implant stability quotient: An in vitro study. J. Clin. Med. 2023, 12, 4190.
13. da Silva Brum, I.; Elias, C.N.; Lopes, J.C.A.; Frigo, L.; dos Santos, P.G.P.; de Carvalho, J.J. Clinical Analysis of the Influence of Surface Roughness in the Primary Stability and Osseointegration of Dental Implants: Study in Humans. Coatings 2024, 14, 951. https://doi.org/10.3390/coatings14080951
14. Joshi, K.; Patil, B. Prediction of surface roughness by machine vision using principal components based regression analysis. Procedia Computer Science, 2020, 167, 382–391. https://doi.org/10.1016/j.procs.2020.03.242
15. Sun, Q.; Mu, X.; Xu, J.; Sun, W.; Wang, L.; Yuan, Y. Substitutability analysis of a numerically simulated surface and an actual rough surface. AIP Adv. 2018, 8(8).
16. Davim P.J. (Ed.), Surface integrity in machining, Springer, London, 2010.
17. Abellán-Nebot, J.V.; Vila Pastor, C.; Siller, H.R. A review of the factors influencing surface roughness in machining and their impact on sustainability. Sustainability 2024, 16, 1917. https://doi.org/10.3390/su16051917
18. Ramezani, M.; Mohd Ripin, Z.; Pasang, T.; Jiang, C.-P. Surface engineering of metals: techniques, characterizations and applications. Metals 2023, 13, 1299. https://doi.org/10.3390/met13071299
19. Ruzova, T.A.; Haddadi, B. Surface roughness and its measurement methods - Analytical review, Results in Surfaces and Interfaces, 2025, 19, 100441. https://doi.org/10.1016/j.rsurfi.2025.100441
20. Tagowski, M.; Chmielik, I.P. The effect of surface preparation on result deviations during roughness measurements using the contact method. Appl. Sci. 2024, 14, 9849. https://doi.org/10.3390/app14219849
21. Stępień, K.; Makieła, W.; Świderski, J. The study of the influence of the tracing speed on the result of surface roughness measurement using the tactile method. Appl. Sci. 2023, 13, 12659. https://doi.org/10.3390/app132312659
22. Lishchenko, N.; O'Donnell, G.E.; Culleton, M. Contactless method for measurement of surface roughness based on a chromatic confocal sensor. Machines 2023, 11, 836. https://doi.org/10.3390/machines11080836
23. Aulbach, L.; Salazar Bloise, F.; Lu, M.; Koch, A.W. Non-contact surface roughness measurement by implementation of a spatial light modulator. Sensors 2017, 17, 596. https://doi.org/10.3390/s17030596
24. Caja García, J.; Sanz Lobera, A.; Maresca, P.; Fernández Pareja, T.; Wang, C. Some Considerations about the use of contact and confocal microscopy methods in surface texture measurement. Materials 2018, 11, 1484. https://doi.org/10.3390/ma11081484
25. Palová, K.; Kelemenová, T.; Kelemen, M. Measuring procedures for evaluating the surface roughness of machined parts. Appl. Sci. 2023, 13, 9385. https://doi.org/10.3390/app13169385
26. Pawlus, P.; Reizer, R.; Wieczorowski, M.; Zelasko, W. The effects of selected measurement errors on surface texture parameters. Materials 2022, 15, 4758. https://doi.org/10.3390/ma15144758
27. Feng, B. Effects of surface roughness on scratch resistance and stress-strain fields during scratch tests. AIP Adv. 2017, 7, 035217.
28. dos Santos Motta Neto, W.; Leal, J.E.S.; Arantes, L.J. et al. The effect of stylus tip radius on Ra, Rq, Rp, Rv, and Rt parameters in turned and milled samples. Int J Adv Manuf Technol 2018, 99, 1979–1992. https://doi.org/10.1007/s00170-018-2630-5
29. Song, J.; Renegar, T.B.; Soons, J.; Muralikrishnan, B.; Villarrubia, J.; Zheng, A., Vorburger, T.V. The effect of tip size on the measured Ra of surface roughness specimens with rectangular profiles. Precis Eng 2014, 3(8), 217–220. https://doi.org/10.1016/j.precisioneng. 2013.07.001
30. Lee, D.-H.; Cho, N.-G. Assessment of surface profile data acquired by a stylus profilometer. Meas Sci Technol. 2012, 23, 105601. https://doi.org/10.1088/0957-0233/23/10/105601
31. Dobes, J.; Leal, J.E.S.; Profeta, J. et al. Effect of mechanical vibration on Ra, Rq, Rz, and Rt roughness parameters. Int J Adv Manuf Technol 2017, 92, 393–406. https://doi.org/10.1007/s00170-017-0137-0

32. Fang, H.; Xu, B.; Yin, D.; Zhao, S. A method to control dynamic errors of the stylus-based probing system for the surface form measurement of microstructures, Journal of Nanomaterials, 2016, 3727514, 8. https://doi.org/10.1155/2016/3727514
33. Karegoudra, S.; Yendapalli, V. A systematic review on non-contact methods to estimate the surface roughness, Materials Today: Proceedings, 2024, 100, 75–92. https://doi.org/10.1016/j.matpr.2023.05.197
34. Ružbarský, J. The influence of the wavelength of laser light on the non-contact measurement of the roughness of shiny cut surfaces on stainless steel A304 material. Appl. Sci. 2024, 14, 2420. https://doi.org/10.3390/app14062420
35. Lishchenko, N.; O'Donnell, G.E.; Culleton, M. Contactless method for measurement of surface roughness based on a chromatic confocal sensor. Machines 2023, 11, 836. https://doi.org/10.3390/machines11080836
36. Likhachev, I.G.; Pustovoy, V.I.; Krasovskiy, V.I. Measurement of the nanoscale roughness using white light interferometry. J Opt Technol. 2017; 8(12)–822. https://doi.org/10.1364/jot.84.000822
37. He, Y.; Zheng, S.; Zhu, F.; Huang, X. Real-Time 3D Reconstruction of Thin Surface Based on Laser Line Scanner. Sensors 2020, 20, 534. https://doi.org/10.3390/s20020534
38. Peng, W.; Xie, J.; Gu, Z.; Liao, Q.; Huang, X. A high performance real-time vision system for curved surface inspection, Optik, 2021, 232, 166514. https://doi.org/10.1016/j.ijleo.2021.166514
39. Antosz, K.; Kozłowski, E.; S̨ep, J.; Prucnal, S. Application of machine learning to the prediction of surface roughness in the milling process on the basis of sensor signals. Materials 2025, 18, 148.
40. Hashmi, A.W.; Mali, H.S.; Meena, A.; Hashmi, M.F.; Bokde, N.D. Surface characteristics measurement using computer vision: A review. CMES-Computer. Mod. Eng. Sci. 2023, 135, 917–1005.
41. Somthong, T.; Yang, Q. Average surface roughness evaluation using 3-source photometric stereo technique. International Journal of Metrology and Quality Engineering, 2016; 7(4), 406. https://doi.org/10.1051/ijmqe/2016024
42. Zamri, R.; Maslan, M.N.; Syed Mohamed, M.S.; Abdullah, L.; Ali, M.; Noorazizi, M.S. The Study of Light Effect on Surface Roughness of Metallic Surface by Using Vision System Technique. 2020. https://doi.org/10.1007/978-981-13-9539-0_49
43. Fu, W.; Zhao, C.; Xue, W. et al. An investigation of the influence of microstructure surface topography on the imaging mechanism to explore super-resolution microstructure. Sci Rep 2022, 12, 13651. https://doi.org/10.1038/s41598-022-17209-9
44. Liu, C.-Y., et al. High-resolution three-dimensional surface imaging microscope based on digital fringe projection technique. Measurement Science Review, Slovak Academy of Sciences, 2020, 20(3), 139–144. https://doi.org/10.2478/msr-2020-0016
45. A Review of the Factors Influencing Surface Roughness in Machining and Their Impact on Sustainabilityabe Rosentritt, M.; Schmutzler, A.; Hahnel, S.; Kurzendorfer-Brose, L. The Influence of CLSM Magnification on the Measured Roughness of Differently Prepared Dental Materials. Materials 2024, 17, 5954. https://doi.org/10.3390/ma17235954
46. Rojewski, M.; Nowinka, B.; Czyżewski, P. 3D optical and mechanical roughness measurements of complex and irregular structures on the basis of polypropylene moldings. Advances in Science and Technology Research Journal. 2024, 18(5), 245–257. https://doi.org/10.12913/22998624/189778
47. Grochalski, K.; Wieczorowski, M.; H'roura, J.; Le Goïc, G. The Optical Aspect of Errors in Measurements of Surface Asperities Using the Optical Profilometry Method. Frontiers in Mechanical Engineering. 2020; 6(12). https://doi.org/10.3389/fmech.2020.00012
48. Elango, V.; Karunamoorthy, L. Effect of lighting conditions in the study of surface roughness by machine vision – an experimental design approach. The International Journal of Advanced Manufacturing Technology, 2007, 33, 487–495.
49. Ružbarský, J. The influence of the wavelength of laser light on the non-contact measurement of the roughness of shiny cut surfaces on stainless steel A304 material. Applied Sciences, 2024, 14(6), 2420.
50. Rosentritt, M.; Schmutzler, A.; Hahnel, S.; Kurzendorfer-Brose, L. The influence of CLSM magnification on the measured roughness of differently prepared dental materials. Materials, 2024, 17(23), 5954.