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Evaluation of contact and optical profilometry in the control of the roughness of curved surfaces of machine parts

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ABSTRACT

Introduction. Roughness measurement of curved machine parts is a critical metrology task, determining the performance characteristics of the components. The contact method introduces systematic error due to the straight-line trajectory of the probe and the plastic deformation of microroughness. Non-contact optical methods eliminate mechanical stress, but their accuracy decreases in areas with a large local inclination angle due to the shadowing effect. The lack of a unified approach to comparing results for curved surfaces limits the ability to tighten tolerances. ***The purpose of the work*** is to conduct a comprehensive comparative analysis of contact and optical profilometry in measuring the roughness of curved surfaces and to develop mathematical models for correcting systematic errors. **Materials and methods.** Experiments were conducted on samples of 0.45% *C* steel and *GG20* cast iron with curvature radii of 2–25 mm and roughness parameters ***Ra*** = 0.1–12.5 µm. Contact measurements were performed using a *TIME TR200* profilometer, while optical measurements were performed using a *Veeco Wyko NT9100* in vertical scanning interferometry and phase shift interferometry modes. *Statistical* processing included *Student's t*-test, correlation, and regression analysis. **Results and discussion.** The error of the contact method at a radius of 2 mm reaches +27.6%, at ***R*** = 25 mm it is no more than +1.4%. The optical method is resistant to curvature, but in areas with high curvature leads to an underestimation of ***Ra*** by 10–15% due to the shadowing effect. For flat surfaces (***Ra*** = 0.8–6.3 µm), there are no significant differences between the methods (***r*** = 0.98). Mathematical models have been developed to correct the influence of temperature, contamination, roughness orientation, vibration, and contact force. ***Conclusions.*** An algorithm for selecting a measurement method is proposed: for radii of curvature less than 10 mm, the optical method with geometric correction is recommended; the contact method is not applicable for radii less than 5 mm. The obtained models can be integrated into the profilometer software for automatic error compensation.

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Introduction

The surface quality of machine components is a critical determinant of their functional performance, including wear resistance, fatigue strength, contact stiffness, sealing capability, and tribological behavior. Surface roughness directly influences friction and wear mechanisms, lubricant film formation, contact stress distribution, and, ultimately, the service life of critical machine elements. Consequently, the reliable

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characterization of surface microgeometry represents one of the fundamental challenges in modern manufacturing engineering and dimensional metrology [1–3].

Currently, contact and optical techniques are the most widely employed methods for surface roughness characterization. Contact profilometry remains the industrial standard owing to its high accuracy, methodological maturity, and ease of implementation [2, 3]. Nevertheless, the physical interaction between the stylus and the measured surface restricts its application to soft materials, ultra-finished surfaces, and components with complex geometries. Additional measurement uncertainties arise from the finite radius of the diamond stylus tip, the applied contact force, and the inherent inability of the stylus to reproduce the complete surface microtopography [4, 5].

The advancement of optical profilometry has substantially expanded the capabilities for non-contact characterization of surface microgeometry. Contemporary optical systems enable high-spatial-resolution measurements while simultaneously reconstructing three-dimensional surface topography [4, 6]. Components exhibiting very low surface roughness or low hardness, such as polymeric and composite materials, are particularly susceptible to mechanical interaction during inspection. Accordingly, non-contact measurement techniques are generally preferred because they eliminate mechanical loading and prevent deformation of the measured surface.

Despite these advantages, the performance of optical techniques strongly depends on the optical characteristics of the measured surface, including its reflectivity, local inclination angle, optical density, and the mechanisms governing the formation of the reflected optical signal [8, 9].

The characterization of roughness on curved surfaces remains one of the most challenging problems in surface metrology. Such geometries include cylindrical and conical components, spherical elements, and free-form surfaces extensively employed in the aerospace, automotive, biomedical, and other high-technology industries.

As the radius of curvature decreases, geometric distortions in roughness measurements become increasingly pronounced. In contact profilometry, these effects are primarily associated with changes in stylus–surface interaction and deviations of the stylus trajectory from the local surface normal. In optical profilometry, increasing angles of light incidence reduce the intensity of the reflected signal, thereby degrading measurement accuracy [10–15].

Although numerous studies have compared contact and optical profilometry, the majority have focused on isolated factors affecting measurement accuracy. Previous investigations have primarily examined the design of profilometer measuring heads, optical system parameters, material properties, or individual measurement conditions [12–16]. Comparatively little attention has been devoted to a comprehensive assessment of the combined effects of surface curvature, manufacturing conditions, and service-related factors on the comparability of measurement results obtained using different inspection techniques.

The significance of this issue has further increased with the widespread adoption of high-performance machining and additive manufacturing technologies, both of which generate complex three-dimensional surface topographies. Variations in processing conditions produce distinct microrelief morphologies characterized by differences in asperity height and shape, which directly influence the results obtained using different measurement methods [16–22]. Under these circumstances, ensuring the comparability of metrological data has become an essential prerequisite for the objective evaluation of machined surface quality.

A review of the available literature indicates that no universal framework currently exists for comprehensively accounting for the combined influence of surface curvature, manufacturing-related factors, and measurement conditions on the results of contact and optical profilometry. Furthermore, the relationship between decreasing curvature radius and measurement error, as well as the potential for mathematical correction of systematic deviations between different measurement techniques, remains insufficiently investigated.

The purpose of the present study is to perform a comparative evaluation of contact and optical profilometry for the assessment of the surface roughness of curved machine components, to quantify the factors influencing measurement uncertainty, and to develop mathematical models that improve the comparability of results obtained using different measurement systems.

The specific objectives are:

– to quantitatively evaluate the systematic errors associated with contact and optical profilometry using specimens with different surface roughness grades and radii of curvature.

– to develop mathematical models describing the influence of manufacturing and operational factors, including temperature, contamination, surface texture orientation, vibration, and contact force, on measurement results.

– to formulate practical recommendations for selecting the most appropriate method for surface roughness assessment.

Methods

Experimental investigations were conducted using specimens manufactured from *0.45% C steel* (medium-carbon structural steel) and *GG-20* gray cast iron subjected to turning, grinding, and milling operations. The measured roughness values were subsequently compared with those of a certified roughness reference specimen. To ensure statistical reliability, each measurement was repeated three times using no fewer than five specimens. Surface roughness was quantified using the arithmetic mean roughness parameter (***Ra***) measured with a contact stylus profilometer. The specimens were then divided into three groups:

Group I – ***Ra*** ≤ 0.4 µm (fine grinding and polishing);

Group II – ***Ra*** = 0.8–6.3 µm (finish turning and grinding);

Group III – ***Ra*** > 6.3 µm (rough turning and milling).

This approach is consistent with the methodology reported in reference [5] and covers a broad range of surface conditions. In addition, cylindrical specimens (shafts and bushings) with radii ***R*** = 2, 5, 10, and 25 mm were manufactured, and their outer surfaces were finish-turned to an average roughness of ***Ra*** ≈ 1.5 µm.

Contact roughness measurements were performed using a *TIME TR200* profilometer equipped with a diamond stylus having a 2 µm tip radius and a 60° included angle. The stylus force was maintained at 0.75 mN by an electronic feedback system. The instrument provided a vertical resolution of 4 nm and a horizontal sampling interval of 0.5 µm, ensuring accurate profile acquisition. The evaluation length ***l*** ranged from 0.8 to 2.5 mm depending on the accuracy class, while the total traverse length corresponded to five evaluation lengths. Low-frequency components (waviness) were removed using a *Gaussian* digital filter with a cutoff corresponding to the selected evaluation length. Before each measurement series, the instrument was calibrated against a certified roughness standard with Ra = 0.5 µm; the calibration error did not exceed 2%. Laboratory conditions were maintained at 20–22 °C and 55–60 % relative humidity.

Three-dimensional surface topography was measured using a *Veeco Wyko NT9100* optical profilometer operating on the principle of optical interferometry. Phase-shifting interferometry with a 50× objective (working distance 3.4 mm) was employed for Group I specimens (***Ra*** ≤ 0.4 µm). Vertical scanning interferometry with 20× or 5× objectives (working distance 6.7 mm) was used for Groups II and III. The acquired data were processed using the *Vision* software package.

To visually demonstrate the influence of the contact method on soft materials, an additional polymethyl methacrylate (*PMMA*, acrylic glass) specimen with a nominal roughness of ***Ra*** = 1.48 µm was examined. This specimen was not included in the quantitative comparison or the main experimental program but served exclusively to visualize scratches and deformation caused by the passage of the profilometer stylus. Measurement conditions were identical (*TIME TR200* profilometer, stylus force 0.75 mN, evaluation length 0.8 mm).

To ensure comparability, all measurements were carried out under constant environmental conditions. Prior to measurement, specimen surfaces were cleaned of cutting-fluid residues and machining debris. This minimized the influence of thermal expansion, surface contamination, and changes in optical properties on the measurement results.

Fig. 1 presents an example of the surface condition after laser processing, illustrating the characteristic microdefects and surface irregularities produced. As illustrated in Fig. 1, optical profilometry provides

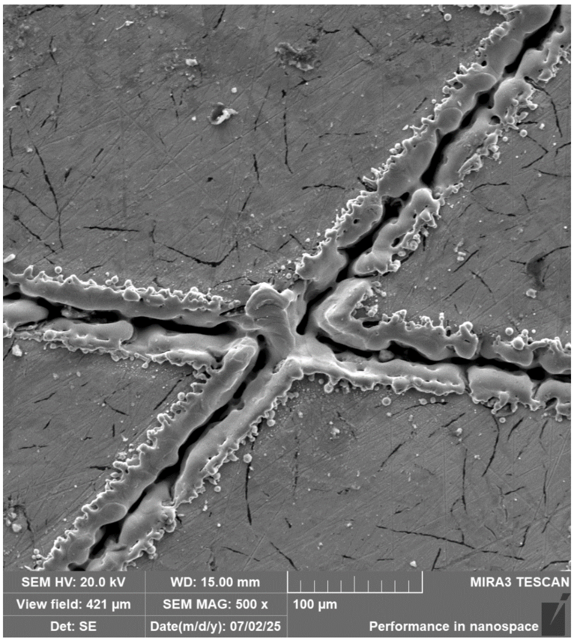

Fig. 1. SEM image of a flat cast iron surface section after laser processing, obtained using a *MIRA3 Tescan* scanning electron microscope

highly detailed surface images with superior spatial resolution. Compared with conventional contact roughness measurements, optical profilometry yields considerably more comprehensive information on surface morphology.

For curved surfaces, curvature and tilt were compensated using the least-squares method, after which the residual profile was filtered using a Gaussian filter, analogous to the contact measurements.

Particular attention was devoted to ensuring the comparability of contact and optical measurements. All specimens were marked, and both techniques were applied to identical surface locations. Each measurement was repeated three times, and the average value was used for analysis. For curved surfaces, the reference values were obtained by scanning electron microscopy using a *MIRA3 Tescan* instrument (measurement uncertainty ≤ 2%). *SEM* was selected as an independent reference technique because it is not included in the pair of methods under comparison (contact and optical profilometry). The influence of curvature on measurement error was evaluated using the relative error **δ** (Eq. 1), where the measured roughness value and the reference roughness value are expressed in µm.

$$\delta = \frac{Ra_{meas} - Ra_{ref}}{Ra_{ref}} \times 100\%, \quad (1)$$

where Ra_{meas} is the measured roughness value, µm; Ra_{ref} is the reference roughness value, µm.

Statistical analysis included calculation of mean values, standard deviations, 95% confidence intervals, and *Student's **t***-test to evaluate the significance of differences between mean values obtained from different regions and specimens. The linear relationship between ***Ra*** values measured by the contact and optical methods was assessed using *Pearson's* correlation coefficient. The dependence of measurement error on the radius of curvature was analyzed using nonlinear regression, and the significance of regression coefficients was evaluated using *Fisher's **F***-test.

To improve the reliability of the findings, each roughness parameter was determined from a series of independent measurements. Data processing included calculation of mean values, determination of absolute and relative deviations between the contact and optical methods for curved surfaces, and evaluation of the influence of surface curvature radius on measurement error. This approach made it possible to identify consistent trends while minimizing the influence of random factors on the final experimental conclusions.

Results and discussion

Quantitative evaluation of the curvature radius effect

Table 1 summarizes the measured surface roughness values (***Ra)*** obtained for the cylindrical specimens.

Table 1

Experimental data on *Ra* roughness measurement considering the effect of the radius of curvature

Radius of curvature ***R*** (mm)	Material	Reference value (*MIRA3*) ***Ra*** (μm)	Contact method, ***Ra*** (μm)	Optical method, ***Ra*** (μm)	Contact method error (%)
2	0.45% *C* steel	1.45	1.85	1.45	+27.6
5	0.45% *C* steel	1.48	1.65	1.48	+11.5
10	0.45% *C* steel	1.46	1.52	1.46	+4.1
25	0.45% *C* steel	1.45	1.47	1.45	+1.4
2	Cast iron	0.98	1.25	0.98	+27.6

The experimental data presented in Table 1 demonstrate that reducing the radius of curvature increases the discrepancy between the results obtained by contact and optical profilometry. The largest deviations were observed for specimens with radii of 2 and 5 mm, where the contact method consistently overestimated Ra compared with the reference values. By contrast, the optical method exhibited excellent agreement with the reference measurements across the entire range of radii investigated.

For both 0*.45% C* steel and *GG-20* cast iron specimens with a radius of curvature of 2 mm, the relative error of the contact method was virtually identical (+27.6 %). This agreement is not attributable to data-processing errors; rather, it reflects the dominant influence of geometric factors at small radii of curvature ($\boldsymbol{R} \leq 5$ mm), where the stylus trajectory deviates from the surface normal during measurement.

The physical and mechanical properties of the investigated materials, including hardness and elastic modulus, had only a negligible effect on measurement accuracy (approximately 1–2%), which is comparable to the random uncertainty of the measurement process.

As the radius of curvature decreases, the likelihood of incomplete reproduction of narrow valleys and local smoothing of profile peaks increases. Surface curvature therefore represents an independent source of systematic measurement error that cannot be eliminated solely by improving the resolution of the measuring system.

Regression analysis revealed a strong correlation between the relative error of the contact method and the radius of curvature ($\boldsymbol{R}^2 = 0.97$). For curved surfaces with radii below 5 mm, the measurement error exceeded 10 % and reached 27.6 % at $\boldsymbol{R} = 2$ mm.

As the radius of curvature increased, the systematic error decreased, confirming the diminishing influence of specimen geometry on the measurement process. Nevertheless, the results also indicate that optical profilometry has inherent limitations when characterizing geometrically complex surfaces. In regions with pronounced local surface slopes, the intensity of the reflected signal decreases, resulting in incomplete reconstruction of the surface topography. This phenomenon is governed by the physics of optical image formation.

Fig. 2 illustrates the relationship between the relative error of the contact method and the radius of curvature for *0.45% C* steel.

The experimental results confirm that the error decreases with increasing radius of curvature, suggesting the existence of a critical radius above which the influence of surface geometry becomes comparable to the intrinsic instrumental uncertainty of the profilometer.

According to the findings reported in Ref. [9], optical profilometers based on reflected-light techniques become less effective when measuring surfaces with pronounced curvature. This limitation gives rise to so-called “blind zones”, leading to systematic underestimation of the ***Ra*** roughness parameter.

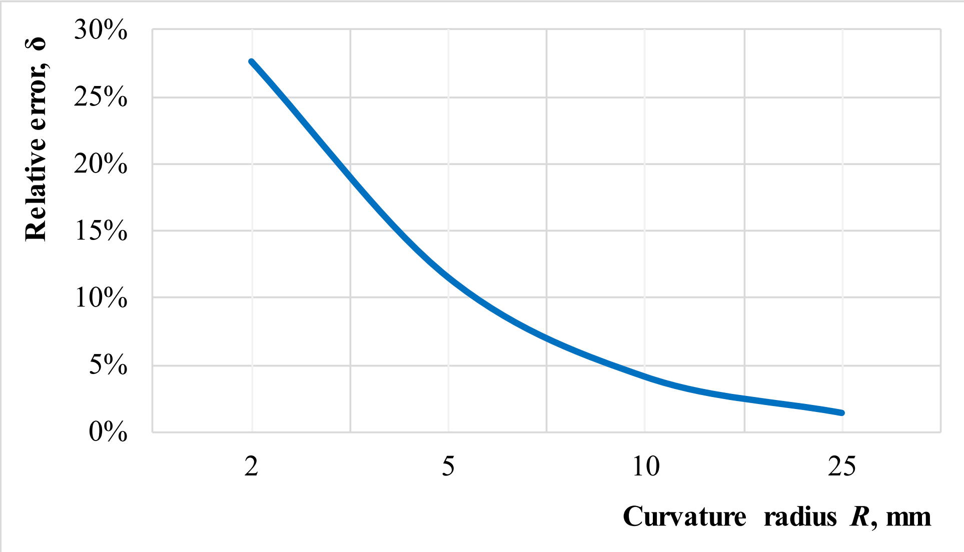

Fig. 2. Dependence of the relative error of the contact method on the Radius of curvature

However, the reduction in the error of the contact method should not be interpreted as evidence that optical profilometry is free from limitations. The principal source of error in contact profilometry is the geometry of the stylus–surface interaction, whereas the accuracy of optical methods is primarily governed by the propagation and reflection of light. Consequently, comparisons between these techniques should consider not only the magnitude of the measurement error but also the fidelity with which the surface profile is reconstructed.

Fig. 3 presents an example of the distortion observed when measuring a surface with a small radius of curvature. The most pronounced distortions occur in the peripheral regions of the cylindrical surface, where the local inclination angle relative to the optical axis is greatest. In these areas, the reflected signal weakens, resulting in incomplete profile reconstruction. In contrast, the central region of the surface, which is oriented almost perpendicular to the measurement direction, is reproduced with high accuracy.

These observations indicate that the limitations inherent in optical profilometry stem from physical mechanisms that are fundamentally distinct from those governing contact profilometry. The former is primarily dictated by the spatial distribution of the optical flux, while the latter is controlled by the kinematic

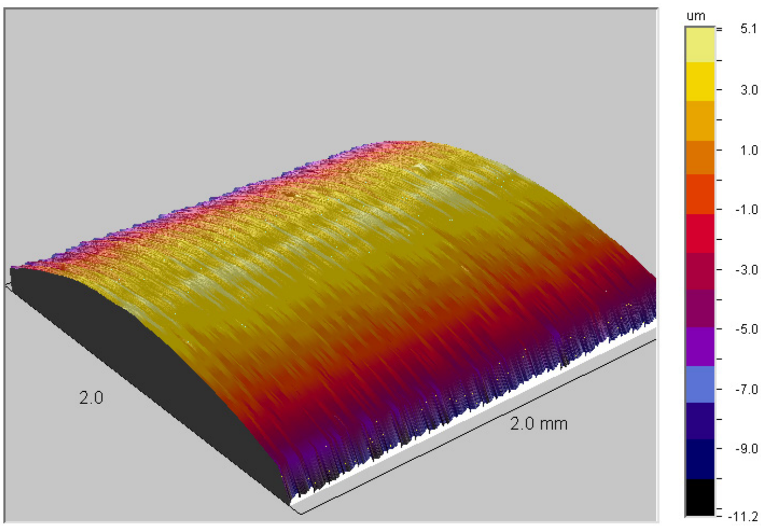

Fig. 3. Measurement of a round cast iron workpiece segment using a *Veeco Wyko NT9100* profilometer

behavior of the stylus. Consequently, the choice of a surface roughness measurement technique should take into account not only the required precision but also the geometric attributes of the surface being examined.

The current analysis confirms that specimen geometry constitutes the predominant source of systematic error attributable to surface curvature. In real industrial environments, however, measurement accuracy is also affected by the machining route, the initial roughness level, and the physical and mechanical characteristics of the workpiece material.

Therefore, the subsequent phase of this work was devoted to a comparative assessment of contact and optical profilometry across various surface texturing methods and a broad spectrum of roughness grades.

Comparison of measurement methods

The results presented above demonstrate that neither measurement technique provides universal advantages under all inspection conditions. The accuracy of surface roughness characterization depends not only on the operating principle of the measuring system but also on a combination of geometric, technological, and physical factors. Accordingly, an objective assessment of the capabilities of contact and optical profilometry requires a comprehensive evaluation of the experimental results while considering the mechanisms responsible for the formation of the surface under investigation.

The measurement results obtained for flat and curved specimens representing different roughness grades are summarized in Table 2.

Table 2

Comparison of contact and optical roughness measurement methods

Roughness class	Machining method	Contact method ***Ra*** (μm)	Optical method ***Ra*** (μm)	Deviation (%)
Ra < 0.4 μm	Fine grinding	0.12	0.11	+9.1
Ra = 0.8–6.3 μm	Grinding	0.85	0.82	+3.7
Ra = 0.8–6.3 μm	Fine turning	1.20	1.25	–4.0
Ra > 6.3 μm	Milling	8.2	7.9	+3.8
Ra > 6.3 μm	Turning	12.5	11.8	+5.9

Analysis of the experimental data demonstrated that the discrepancy between the contact and optical methods is governed not only by the absolute value of the ***Ra*** parameter but also by the mechanism of surface microtopography formation. Even at comparable roughness levels, surfaces produced by different machining processes exhibit distinct spatial morphologies. These differences influence both the interaction between the stylus tip and the surface in contact profilometry and the registration of the reflected optical signal in optical profilometry.

Although ***Ra*** is the most widely used quantitative descriptor of surface roughness, it does not fully characterize the spatial organization of the surface microrelief. Surfaces exhibiting identical ***Ra*** values may differ substantially in asperity geometry, spacing, machining directionality, and the distribution of local peak heights. Consequently, the observed differences between contact and optical profilometry are attributable not only to the magnitude of roughness but also to the surface-generation mechanism associated with the specific machining process.

The findings indicate that the manufacturing process used to generate the investigated surface represents one of the factors contributing to measurement uncertainty.

As the surface morphology transitions from the regular microrelief characteristic of turning to the more irregular topography produced by milling or grinding, the interaction between the measuring system and the surface changes. Consequently, the sensitivity of both contact and optical measurement techniques varies even when comparable ***Ra*** values are obtained.

The experimental results obtained by optical profilometry are presented in Fig. 4. The investigated specimen was manufactured from *GG-20* gray cast iron following a finish-turning operation.

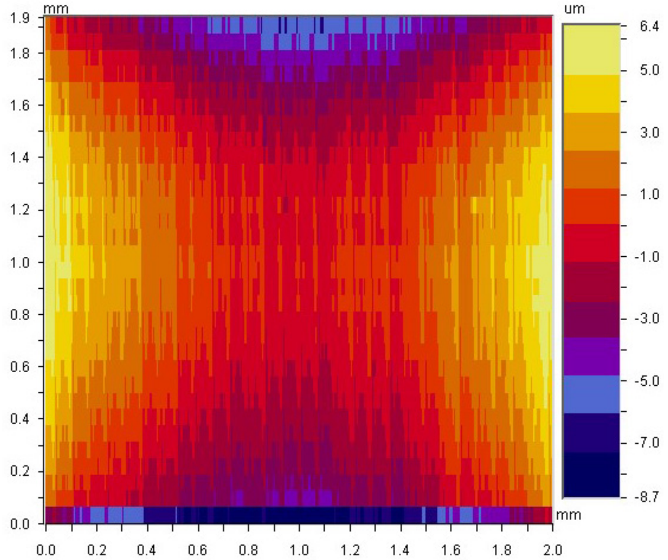

Fig. 4. Measured roughness image of a cast iron workpiece after finish turning, obtained using a *Veeco Wyko NT9100* profilometer

Statistical analysis of the flat surfaces with roughness values within the ***Ra*** = 0.8–6.3 µm range revealed no statistically significant differences between the two measurement techniques. The *Pearson* correlation coefficient was ***r*** = 0.98, indicating excellent agreement between the experimental datasets.

Statistical analysis of the experimental data and evaluation of method agreement

To obtain an objective assessment and determine the statistical significance of differences between the mean values of the surface roughness parameter, *Student's* t-test was employed. Depending on the surface roughness grade, the following statistical relationships were identified.

For surfaces with ***Ra*** < 0.4 µm, corresponding to a high surface finish, *Student's* ***t***-test yielded $t = 2.89$ ($p < 0.05$), indicating a statistically significant difference between the investigated measurement techniques. The *Pearson* correlation coefficient was ***r*** = 0.94, demonstrating a high degree of correlation between the datasets. The standard deviation obtained using the contact method was **σ** = 0.028, which exceeded that of the optical method (**σ** = 0.012). These findings indicate lower measurement repeatability of the contact method when characterizing ultra-smooth surfaces.

For surfaces with ***Ra*** = 0.8–6.3 µm, corresponding to the medium roughness range, *Student's* ***t***-test produced ***t*** = 1.23 (***p*** > 0.05), indicating that no statistically significant differences existed between the measurement methods. The Pearson correlation coefficient reached ***r*** = 0.98, confirming excellent agreement between the experimental results. The coefficient of variation for the contact measurements was 8.2%, whereas the corresponding value for the optical method was 4.1%, demonstrating the superior stability and repeatability of optical profilometry.

For rough surfaces with Ra > 6.3 µm, *Student's* ***t***-test yielded ***t*** = 3.45 (***p*** < 0.01), while the *Pearson* correlation coefficient was ***r*** = 0.96. Under these conditions, the contact method consistently produced values approximately 4–8% higher than those obtained by optical profilometry. This tendency can be attributed to the dynamic characteristics of the contact measuring system as well as to the smoothing effect associated with stylus tracing over pronounced surface irregularities.

Measurements performed using the contact method demonstrated an increase of approximately 7–11% in the measured roughness values for surfaces with a high surface finish, which can be explained by the elastic deformation of surface asperities during stylus traversal [3, 8]. Furthermore, when more compliant materials were examined, localized surface damage in the form of stylus scratches was observed (Fig. 5).

As clearly shown in Fig. 5, contact profilometry can induce surface damage on highly finished surfaces, especially those produced by fine grinding, resulting in overestimation of the measured roughness. Optical profilometry is therefore the preferred method for characterizing ultra-smooth surfaces.

The surface profile following laser processing is presented in Fig. 6.

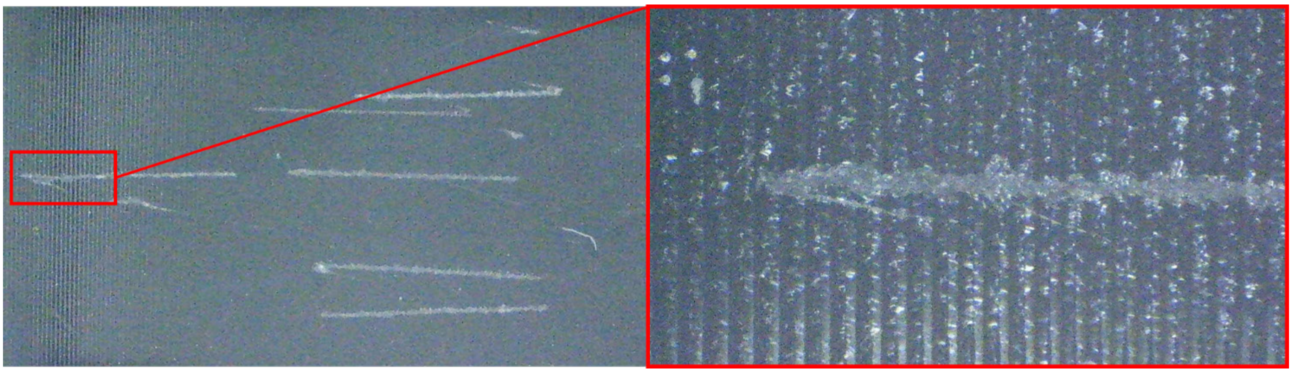

Fig. 5. Stylus needle traces on a plexiglass reference specimen with roughness ***Ra*** = 1.48 µm

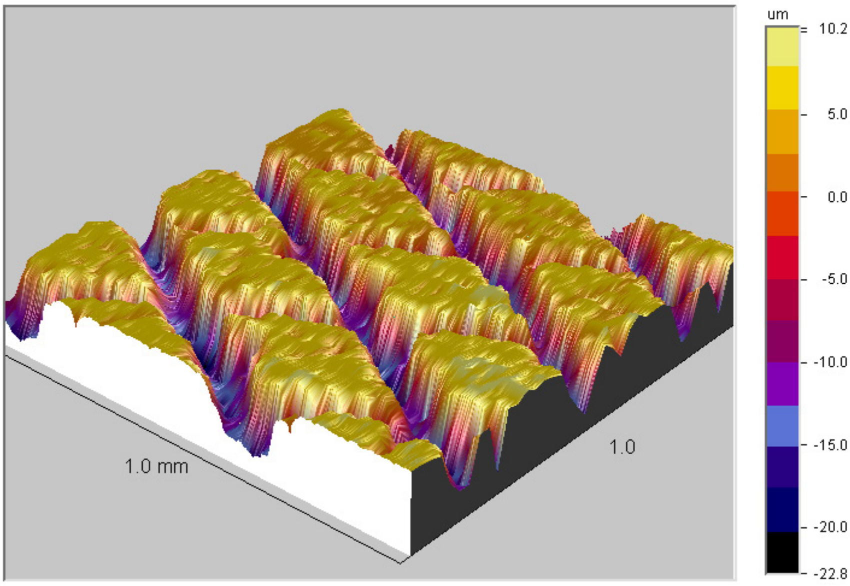

Fig. 6. Profile of a flat cast iron surface obtained after laser processing and measured using a *Veeco Wyko NT9100* profilometer

Fig. 6 illustrates the ability of optical profilometry to capture the three-dimensional distribution of surface micro-irregularities. Unlike conventional contact techniques, optical profilometry yields comprehensive spatial information on surface topography, facilitating a thorough assessment of surface morphology.

A fundamental distinction between contact and optical roughness measurement techniques lies in the method used to reproduce the surface profile. During contact profilometry, the stylus mechanically interacts with the investigated surface, resulting in partial smoothing of sharp asperity peaks. Furthermore, when long evaluation lengths are employed, the measurement process becomes increasingly susceptible to low-frequency disturbances introduced by the mechanical characteristics of the stylus system [16]. Consequently, the applicability of contact profilometry is limited in studies requiring high-resolution characterization of complex surface topography.

By contrast, optical profilometry enables detailed analysis of surface morphology through the identification of spatial harmonic components associated with the manufacturing process. For example, periodic surface features generated by the feed motion during milling can be quantitatively evaluated using optical measurements [8]. This capability is equally important for the investigation of surfaces exhibiting pronounced directional texture, including those produced by laser-based additive manufacturing technologies, where characteristic surface patterns are formed during material deposition [5, 10, 19, 20].

The results obtained from measuring the groove pitch after finish face milling using optical profilometry are presented in Fig. 7.

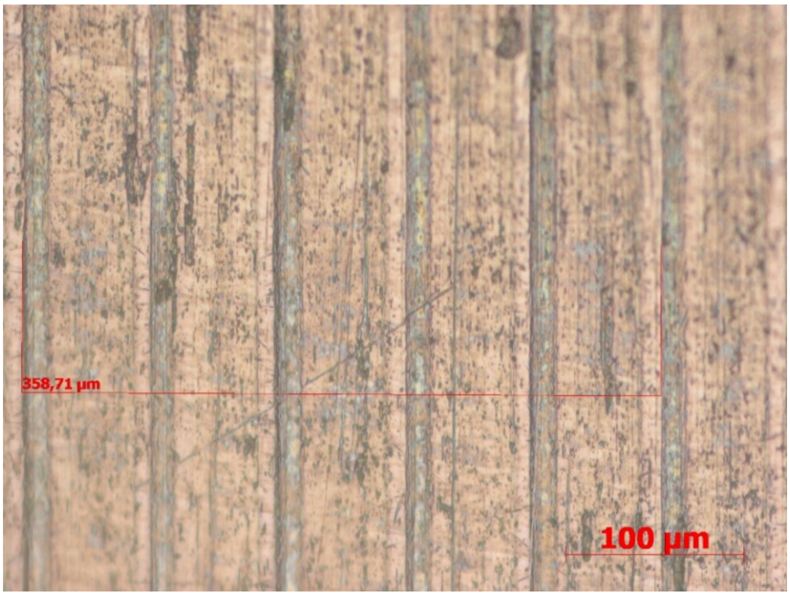

Fig. 7. Measurement of groove pitch after finish face milling of a 0.45% *C* steel part

Fig. 7 illustrates one of the principal advantages of optical profilometry over conventional contact measurement techniques. In addition to determining conventional roughness parameters, optical profilometry enables comprehensive three-dimensional analysis of surface topography, including quantitative evaluation of spatial texture characteristics, periodic surface features, and the geometric relationships between individual microstructural elements.

Such capabilities significantly expand the range of metrological information available for assessing the quality of machined surfaces and provide a more comprehensive understanding of the mechanisms governing surface formation during manufacturing processes.

Mathematical modeling of measurement errors

Based on the experimental data and the relationships reported in Refs. [1, 9, 20], mathematical models are proposed to compensate for the influence of the following factors on the surface roughness parameter.

1. Thermal expansion of the workpiece results in a relative variation of the roughness parameter ***Ra***. Accordingly, a temperature correction should be introduced using Eq. (2) [7]:

$$Ra^{corr} = \frac{Ra^{meas}}{\left[1 + \alpha(T - T_0)\right]}, \tag{2}$$

where Ra^{corr} is the corrected roughness value (μm); Ra^{meas} is the measured roughness value (μm); α is the coefficient of linear thermal expansion (1/°C); T is the workpiece temperature at the time of measurement (°C); T_0 is the reference temperature (20 °C).

The relative temperature error of the measuring instrument, $\boldsymbol{K_p}$, empirically established for *0.45% C* steel within the temperature range of 20–45 °C, is determined by Eq. (3):

$$K_p = -0.0002(T_p - T_0)^2 + 0.0015(T_p - T_0), \tag{3}$$

where T_p is the instrument temperature during measurement (°C); T_0 is the reference temperature (20 °C).

Equation (3) accounts for temperature-induced variations in the measuring system, thereby improving compensation of the measurement error.

2. The relative measurement error associated with surface contamination is described by the exponential relationship given in Eq. (4) [21]:

$$\delta_{cont} = A\left(1 - e^{(-kh)}\right), \tag{4}$$

where δ_{cont} is the relative measurement error caused by the contamination layer (%); A is the maximum error (40% for emulsion and 20% for oil) (%); k is an empirical coefficient (0.8–1.2 μm^{-1}); h is the thickness of the contamination layer (μm).

The contamination correction coefficient $\boldsymbol{K_{cont}}$ is subsequently calculated using Eq. (5):

$$K_{cont} = \frac{1}{1 + \delta_{cont} / 100}, \quad (5)$$

3. The influence of the orientation of surface asperities (the angle $\boldsymbol{\theta}$ between the stylus trajectory and the machining marks) on the relative roughness measurement error is described by Eq. (6):

$$\delta_{or} = \Delta \cos \theta_{max}, \quad (6)$$

where δ_{or} is the relative orientation-induced measurement error (%); θ is the angle between the stylus travel direction and the surface asperities (degrees); Δ_{max} equals –0.45 for turning and –0.35 for grinding.

The orientation correction coefficient $\boldsymbol{K_{or}}$ is determined using Eq. (7):

$$K_{or} = \frac{1}{1 + \delta_{or}}, \quad (7)$$

4. The influence of vibration on the measured roughness parameter ***Ra*** is described by Eq. (8) [22]:

$$K_{vibr} = \frac{1}{1 + \gamma A_v f_v}, \quad (8)$$

where γ is the sensitivity coefficient (0.01–0.05 μm^{-1}·Hz^{-1}); A_v is the vibration amplitude (μm); f_v is the vibration frequency (Hz).

5. Influence of the mechanical properties of the measured material. The optimum stylus force, $\boldsymbol{F_{opt}}$, required to minimize plastic deformation is determined using Eq. (9):

$$F_{opt} = \frac{k \cdot H^2 \cdot R^2}{E}, \quad (9)$$

where F_{opt} is the optimum stylus force (mN); H is the *Vickers* hardness (MPa); E is the *Young's* modulus (GPa); k is an empirical coefficient (8–12); R is the stylus tip radius (mm).

The relative deformation error, $\boldsymbol{\delta_{def}}$, is then determined using Eq. (10):

$$\delta_{def} = \frac{F \cdot k_{pl}}{H \cdot Ra^{meas}}, \quad (10)$$

where F is the stylus force (mN); k_{pl} is the coefficient accounting for plastic deformation; H is the *Vickers* hardness (MPa); Ra^{meas} is the measured roughness value (μm).

The deformation correction coefficient, $\boldsymbol{K_{def}}$, accounting for plastic deformation of surface micro-asperities caused by the stylus contact force, is calculated using Eq. (11):

$$K_{def} = \frac{1}{1 + \delta_{def}}, \quad (11)$$

Considering the above relationships, the corrected roughness parameter is determined according to Eq. (12):

$$Ra = Ra^{corr} (1 \pm K_p) K_{count} K_{or} K_{vibr} K_{def}, \quad (12)$$

The proposed mathematical relationships incorporate the most significant factors contributing to the systematic component of measurement uncertainty. Their practical implementation is feasible provided that the coefficients are physically justified and their adequacy is confirmed experimentally.

The relationships developed in this study can be implemented in measurement-system software for automatic compensation of roughness parameters during component inspection. This approach improves the reliability of surface roughness evaluation without requiring modifications to conventional measuring equipment and broadens the practical applicability of the proposed model under industrial operating conditions.

Justification of empirical coefficients and validation of the mathematical models

To eliminate subjectivity and confirm the physical validity of the empirically obtained coefficients, a preliminary calibration was performed using experimental data obtained through a multifactor design of experiments.

Each empirical coefficient was calibrated through separate multifactor experiments in which only one investigated parameter was varied while all other conditions remained constant. Each coefficient was determined from at least three series of measurements with fivefold repetition, ensuring the statistical reliability of the results. The justification of the key coefficients used in the model is presented below.

1. The data presented in Model (6) indicate that the orientation coefficient was $\mathbf{\Delta}_{max}$ = –0.45 for the turning process and $\mathbf{\Delta}_{max}$ = –0.35 for grinding. These values were obtained using the least-squares method based on regression analysis of the experimental dependence of the relative error $\boldsymbol{\delta}_{or}$ on the angle $\boldsymbol{\theta}$ between the probe travel direction and the machining marks (0°–90°).

For example, during turning, at $\boldsymbol{\theta}$ = 0°, when the probe moved along the machining marks, the relative measurement error was –2 to –3%. At $\boldsymbol{\theta}$ = 90°, the relative error reached –42 to –45%. Least-squares approximation yielded $\mathbf{\Delta}_{max}$ = –0.45 with a coefficient of determination $\boldsymbol{R}^2$ = 0.94. Similarly, $\mathbf{\Delta}_{max}$ = –0.35 ($\boldsymbol{R}^2$ = 0.91) was obtained for grinding. The experimental dataset included 15 measurements at each angle for three different materials.

2. Stylus force coefficient k = 8–12 in Equation (9). This coefficient was derived from the *Hertzian* contact solution for the “diamond stylus–steel (cast iron)” pair and accounts for the effective contact area for a stylus tip radius of 2 μm. Calibration was performed by varying the probing force from 0.5 to 1.5 mN on specimens made of *0.45% C* steel, *EN AW-2024* aluminum alloy, and *CW614N* brass to confirm its universality.

3. Contamination model coefficients ($\boldsymbol{A}$, $\boldsymbol{k}$) in Equation (4). Values of $\boldsymbol{A}$ = 40% (cutting-fluid emulsion) and $\boldsymbol{A}$ = 20% (oil) were obtained by approximating the data in Table 1. These values correlate with the contamination layer thickness $\boldsymbol{h}$ measured by optical microscopy on metallographic cross-sections.

Analysis of the model coefficients shows that the system is most sensitive to changes in the surface curvature radius. Even a slight reduction in radius results in a much greater increase in error than changes in the other factors. Temperature, surface contamination, and stylus wear have a less pronounced effect and mainly contribute to the systematic component of the error. These results confirm that the geometric characteristics of the inspected surface are the dominant factor in selecting a roughness measurement method.

The coefficients used in the mathematical models were obtained empirically through experimental studies. The resulting relationships can be regarded as mathematical models that describe the physical regularities governing the influence of surface geometry and technological and operational conditions on the accuracy of roughness measurements.

The adequacy of Mathematical Models (2)–(12) was verified using an independent control sample of *0.45% C* steel specimens after finish turning with a curvature radius of $\boldsymbol{R}$ = 2 mm. Table 3 presents the verification results.

The data in Table 3 demonstrate that the integrated correction model significantly reduces the systematic error of contact measurements. For specimens with $\boldsymbol{R}$ = 2 mm, the deviation from the reference values decreases from 25–27 % to less than 3%.

To evaluate the effectiveness of the proposed model over the entire range of conditions, verification results were additionally analyzed using 15 specimens with different curvature radii (2, 5, 10, and 25 mm) and three roughness classes, followed by determination of the error reduction $\boldsymbol{\delta}$ for each specimen.

Table 3

Verification results of the correction model on a test sample

Measurement method	Measured ***Ra*** (μm)	Corrected ***Ra*** (μm)	Reference method (*MIRA3*) (μm)	Deviation (before / after correction) (%)
Contact (*TIME TR200*)	1.82	1.49	1.45	+25.0 / +2.7
Optical (*Veeco Wyko NT9100*)	1.85	1.46	1.45	+27.6 / +0.7

For the entire sample, the average reduction was 6.2 ± 1.1%. This result supports the conclusion that the systematic error is reduced by approximately 5–7%. The confidence interval was calculated at the 95% confidence level using *Student's* ***t***-test.

The achieved agreement between measured and corrected values confirms the validity of the proposed mathematical model. The greatest correction effect was observed for specimens with a small curvature radius, where the geometric component of the measurement error predominates.

For surfaces with a larger curvature radius, the influence of the correction coefficients decreased, which is consistent with the previously established experimental trends. These results demonstrate the practical applicability of the developed model for the metrological support of measurement of components with complex geometries.

The results indicate that the integrated model enables a transition from a qualitative assessment of error sources to their quantitative description. This makes it possible to predict the expected measurement error before performing measurements and to select the most appropriate measurement method according to the geometry of the investigated surface.

The findings of the present study demonstrate that no universal roughness measurement method is equally effective under all measurement conditions. The selection of a measurement system should take into account the component geometry, roughness range, material properties, and required measurement accuracy. Therefore, the final stage of the study involved the development of practical recommendations for selecting an appropriate measurement method for various manufacturing conditions.

Algorithm for selecting a measurement method

On the basis of the experimental findings, practical guidelines for the selection of an appropriate surface roughness measurement technique were established (Table 4).

These observations can be attributed to the nature of the contact interaction between the stylus and the surface. In the case of softer materials, localized elastic–plastic deformation of individual asperity summits

Table 4

Recommendations for choosing a roughness measurement method

Roughness class / surface type	Recommended method	Note
Ra < 0.4 μm. Soft/brittle materials	Optical	Eliminates surface damage; stylus pressure is comparable to material hardness
Ra = 0.8–6.3 μm. Flat surfaces	Contact and optical	Optical method is preferred for detailed profile analysis
Curved surfaces (***R*** < 10 mm)	Optical with correction	Contact method requires mandatory correction using the proposed model
Curved surfaces (***R*** < 5 mm)	Optical	Contact method is inapplicable due to geometric distortions
Spatial frequency analysis	Optical	Required for studying directional machining marks and surfaces obtained by additive technologies

may take place, whereas for harder materials, the contact remains essentially elastic. Nevertheless, the experimental evidence indicates that, over the range of materials investigated, this effect is substantially less influential than the geometric characteristics of the surface.

Conclusions

1. A comparative investigation of contact and optical methods for measuring the roughness of curved surfaces was carried out. The surface curvature radius was identified as the primary factor responsible for discrepancies between measurement results. As the curvature radius decreased, the systematic error of contact profilometry increased, reaching +27.6% for specimens with ***R*** = 2 mm, whereas at ***R*** = 25 mm it did not exceed +1.4%. The optical method exhibited substantially lower sensitivity to surface curvature. Nevertheless, in regions with large local inclination angles, the optical technique underestimated the ***Ra*** roughness parameter by 10–15 % owing to the shadowing effect.

2. A geometric factor was identified whose influence on the measurement results significantly exceeded that of the physical and mechanical properties of the specimen material. Nearly identical relative errors were obtained for *0.45% C* steel and *GG-20* gray cast iron specimens (+27.6% at ***R*** = 2 mm), confirming the dominant role of surface geometry in the formation of measurement error.

For flat surfaces with ***Ra*** = 0.8–6.3 μm, no statistically significant differences were found between the contact and optical methods (***r*** = 0.98, ***t*** = 1.23, ***p*** > 0.05). However, for smooth surfaces (***Ra*** < 0.4 μm), the contact method overestimated the measured values by 7–11% because of elastic deformation of surface asperities.

3. An integrated mathematical model was developed that accounts for the influence of the curvature radius, machining method, and operational factors, including specimen temperature, surface contamination, machining-mark orientation, vibration, and probe contact force, all of which affect the accuracy of surface roughness measurements.

The empirical coefficients were substantiated using a multifactor design of experiments and the *Hertzian* contact model. Validation of the proposed model using an independent dataset demonstrated good agreement between calculated and experimental results. For specimens with a small curvature radius (***R*** = 2 mm), the proposed correction reduced the discrepancy from 25–27% to below 3%. Across the entire investigated range of conditions (***R*** = 2–25 mm, ***Ra*** = 0.1–12.5 μm), the average reduction in the systematic error component was 5–7%, as confirmed by statistical analysis.

4. The obtained results demonstrate that application of the proposed model improves the comparability of contact and optical profilometry and provides a more reliable evaluation of the roughness parameters of components with complex geometries. The proposed approach can be employed in the metrological support of manufacturing processes and in the development of software tools for automated correction of measurement results.

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Conflicts of Interest

The authors declare no conflict of interest.