euspen's 26th International Conference & Exhibition, Krakow, PL, June 2026
www.euspen.eu

Multisensory and multiscale characterization of selected technological surfaces using optical methods

Michał Jakubowicz[1], Karol Grochalski[1], Tomasz Bartkowiak[1], Bartosz Gapiński[1], Michał Wieczorowski[1]

[1] *Poznan University of Technology, Jacka Rychlewskiego Street 1, 61-131 Poznan*

michal.jakubowicz@put.poznan.pl

Abstract
Contemporary industry, regardless of sector, places increasingly high demands on the precision and quality of manufactured components. One of the key aspects of quality control is the measurement of surface roughness and topography, which provides essential information about the functional properties and durability of products. Traditional measurement methods, based mainly on contact profilometry, although still widely used, have limitations related to time consumption, potential interference with the surface of the tested component, and restricted spatial analysis capabilities. The dynamic development of optical technologies enables the application of modern, non-contact measurement methods, which not only ensure high accuracy but also allow three-dimensional analysis of the geometric structure of surfaces. This paper presents a methodology for investigating the topography of selected technological surfaces using multisensory and multiscale optical techniques. The analysis covers measurement data obtained from various manufacturing and processing methods, acquired with tools such as focus variation microscopy, white light interferometry, and confocal profilometry. The research included both quantitative and qualitative assessments, considering different measurement parameters and data filtering procedures. The implementation also addresses the complex issue of how the type and degree of data filtering influence the metrological parameters measured with different techniques. The results obtained were compared with those from classical contact profilometry, allowing a comparative evaluation of the effectiveness and applicability of the analysed methods. The collected data constitute a valuable source of information that supports a comprehensive assessment of the geometric structure of the examined surfaces. The use of optical methods paves the way for fast, precise, and non-destructive quality evaluation, which is crucial for the further development of production processes across various industries

multisensors measurement systems; optical metrology; roughness; surfaces topography

1. Introduction

Contemporary industry, regardless of the area of application, is characterized by a systematic increase in requirements for the precision and quality of manufactured components. One of the key aspects of quality assessment is the measurement of surface roughness and topography, which provides essential information on the functional properties and service life of products across various fields [1-5]. Traditional measurement methods, based primarily on contact profilometry techniques [6], despite their widespread use, exhibit certain limitations, including high time consumption [7], the risk of affecting the measured surface, and restricted spatial analysis capabilities [8-10]. The dynamic development of optical technologies enables the implementation of modern non-contact measurement methods that ensure high accuracy and allow for three-dimensional analysis of surface geometric structures [11].

Non-contact methods, such as optical profilometry, offer several advantages over contact techniques. They are generally faster, non-destructive, and capable of providing detailed spatial analysis without the risk of surface damage [12, 13]. These methods involve interferometry, structured light, and digital holography to capture surface profiles accurately and efficiently [14-16]. The most popular non-contact methods for measuring the geometric structure of a surface include coherence scanning interferometry [17], imaging confocal microscopy [18] and focus variation microscopy [19]. Non-contact techniques are particularly beneficial in applications requiring high precision and minimal interference with the surface, such as in medical, aerospace, and advanced manufacturing fields [20, 21]. In conclusion, while contact profilometry techniques are widely used, their limitations in terms of time consumption, risk of surface impact, and spatial analysis capabilities make non-contact methods a preferable alternative in many advanced applications.

Advanced surface characterization increasingly relies on multisensory and multiscale approaches to capture the full geometric complexity of engineering surfaces [22]. Surface features occur across a wide range of spatial scales, from nanometric roughness to macroscopic form, and no single measurement technique can provide a complete and reliable description of topography. Multisensory strategies, which combine contact and non-contact techniques, exploit the complementary strengths of individual sensors to improve measurement accuracy, robustness, and reliability [23]. Simultaneously, multiscale analysis enables surface features to be evaluated according to their spatial extent and functional relevance, allowing the separation of roughness, waviness, and form. By integrating multisensory data acquisition with multiscale analytical methods and advanced mathematical and statistical tools, a comprehensive framework for surface assessment is established. Such approaches are essential for understanding, quantifying, and optimizing surface properties across diverse engineering applications, from precision manufacturing [24] to heritage science [25], and for enhancing the correlation between measured topography and functional performance.

Despite the dynamic development of optical methods for surface topography measurement, the literature still lacks clear and systematic comparisons of different optical techniques. The influence of applied data filtering methods on the values of metrological parameters remains insufficiently understood, which hinders their unambiguous interpretation. In addition, there is a need to relate results obtained using optical methods to classical measurement techniques in order to ensure consistency and reliability in surface evaluation.

2. Methodology

2.1. Materials

The investigated specimens were isotropic, textured surfaces produced by sandblasting at working pressures of 2 (2-BAR), 4 (4-BAR, and 6 bar (6-BAR). The parts were made of 7075 aluminium alloy. Each specimen was marked by micromachining a 4.0 mm × 4.0 mm outline, with the analyzed texture located at its centre. This step was essential to ensure unambiguous orientation and identification of the measurement area for the surface texture measurement techniques and instruments considered. Figure 1 shows the overview of analyzed surfaces.

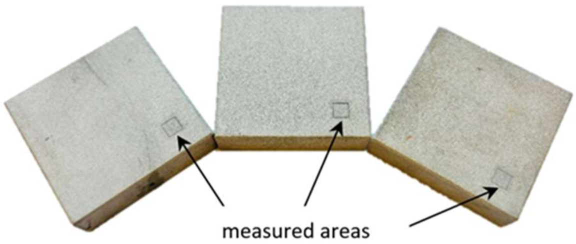

Figure 1. View of samples made of 7075 aluminum alloy

The measured area for each part was 4.0 mm × 4.0 mm. The measurement data were levelled to remove form error, filtered using an S–L Gaussian filter, truncated at a maximum material ratio of 0.5%, and completed by filling unmeasured points. The processed areas were then subjected to qualitative (non-parametric) and quantitative (parametric) analyses

Analysis of surface topography involved comparing areal parameters, specifically Sa (arithmetic mean height), Sq (root mean square height), Sku (kurtosis of surface height distribution), Sk (core roughness depth), Spk (reduced peak height), and Svk (reduced valley depth), which together describe the average roughness, peak and valley characteristics, and the sharpness or flatness of the surface.

The relative error δ_{Rel} was adopted as a measure of measurement convergence and was defined as the quotient of the difference between the measurement result obtained using one of the optical methods and that obtained using the reference (stylus) device, divided by the value obtained using the reference device:

$$\delta_{Rel} = \frac{A - B}{B} \cdot 100\% \tag{1}$$

where:

A – value of the selected surface topography parameter obtained by one of the optical methods (confocal profilometry, focus variation, and white-light interferometry).

B – value of the selected surface topography parameter using the Hommel-Etamic Roundscan T8000 device (reference device).

This allowed for comparison of the tested surfaces and their evaluation in terms of various measurement techniques.

2.2. Methods for analyzing the structure

The approach here was focused on analyzing the similarity of selected areal surface parameters across the applied measurement techniques. The following methods were considered: contact (stylus) technique as the reference method, confocal profilometry, focus variation (FV), and white-light interferometry (WLI).

Contact (stylus) profilometry was adopted as the reference. The Hommel-Etamic T8000 (Jenoptik Industrial Metrology Germany GmbH) is a system for measuring surface topography using a profile-based approach; when combined with a motorised traversing stage, it also enables three-dimensional (3D) topography measurements. The instrument was equipped with a TKU300 measuring head. A diamond stylus tip with a 90° apex angle and a 2 µm tip radius was used for the measurements. The profilometer operated within a measurement range of ±80 µm.

Another technique used in this study was the non-contact AltiSurf 520 profilometer (Altimet). It is a non-contact system for 3D topography measurement, in which surface height is determined optically based on the confocality condition—typically implemented in a chromatic configuration. The operating principle relies on the fact that different wavelengths are brought to focus at different heights, and the surface position along the Z-axis is estimated from the spectrum of light returning to the detector [26]. In this study, a CL1 objective with a measurement range of 130 µm was used.

Surface topography measurements were also performed using an Alicona µCMM optical micro-measuring machine (Alicona Imaging GmbH). This device enables precise measurement of dimensions, positional and shape deviations, as well as surface topography. This system is based on the principle of focus variation microscopy, which involves analyzing the sharpness of an optical image to assess changes in surface features [27].

Another instrument employed in this study is a multisensor system based on an optical machine. Additional measurement heads were incorporated, enabling observations at both micro- and nanoscale levels. The Optiv Reference 763 Dual Z (Hexagon AB) features a granite portal-type construction with a fixed portal and two independent vertical spindles, which support a vision sensor, a scanning contact sensor, and a white light interferometer (WLI). The WLI functions as a coherent scanning interferometer (CSI), as defined by ISO 25178-604 [28]. In interferometric systems of this type, white light interferometers are used instead of a single-wavelength light source. The entire system is controlled using PC-DMIS CAD++ software, which, in addition to providing numerous measurement options, allows data acquisition from multiple sensors within a common coordinate system.

For clarity in the following sections of the article, the measurement methods used in the study are represented using a simplified notation, as presented in Table 1.

Table 1 Symbols used for devices used in research

Device	Symbol
Hommel-Etamic T8000	I-90N
AltiSurf 520	CL-1
Alicona µCMM	A20×
Optiv Reference 763 Dual Z	WLI20×

For the optical methods (Alicona µCMM and Optiv Reference 763 Dual Z), the same 20× magnification was applied. In both techniques, stitching was used. For both the Alicona microscope and the Optiv device, the overlap between adjacent measurement fields was set to 30%.

An important factor affecting the comparability of the techniques is the resolution, or equivalently the signal sampling density. For Focus Variation (FV) microscopy, the lateral resolution was 500 nm and the vertical (Z-axis) resolution was 70 nm. Analogous parameters were applied for the WLI technique. For the profile-based methods, the spacing (step) between consecutive points along a single profile was 0.7 µm for both the contact profilometer (T8000) and the confocal profilometer (AltiSurf 520), while the signal was sampled at 10,000 points per measurement trace. The obtained datasets underwent parametric analysis using MountainsMap software, facilitating the extraction of information regarding various parameters of the geometric structure for each of the tested surfaces.

3. Results and discussion

Surface measurements performed using the considered measurement techniques enabled their graphical visualisation. This allows for rapid comparison and the identification of similarities. A selected example of a three-dimensional surface (6-BAR – Alicona µCMM) is shown in figure 2.

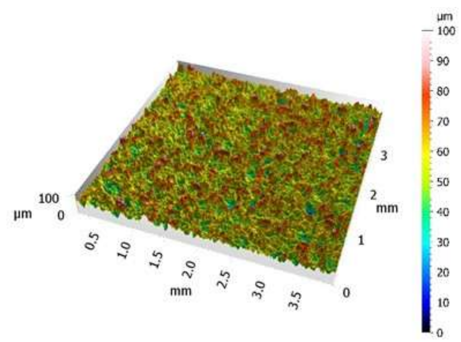

Figure 2. View of 3D representative sample texture (6-BAR)

The recorded data also enabled a parametric assessment of the surface structure for selected parameters depending on the applied measurement technique. Figure 3 presents selected areal parameters (from the full set of surface parameters), which are described later in the text.

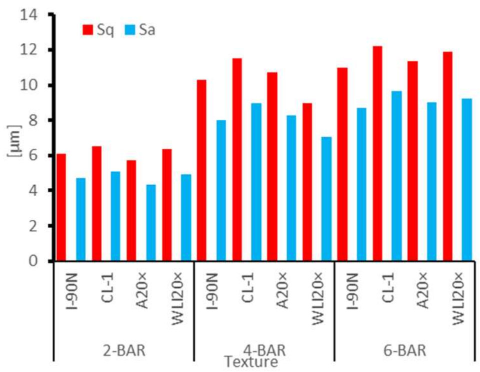

Figure 3. Selected surface parameters for the tested measurement techniques

Figure 3 presents the values of the areal surface texture parameters Sa and Sq obtained for three isotropic surfaces measured using four measurement techniques. Regardless of the structure and the technique, Sq takes higher values than Sa, which is typical because Sq is more sensitive to larger height deviations than Sa (which is based on averaged values). Within each structure, differences resulting from the applied measurement technique are also observed. For all three structures, confocal profilometry (CL-1) yields the highest Sa and Sq values, suggesting that it captures a greater contribution of components with large deviations (i.e., higher sensitivity to peaks and valleys) compared to the other methods. At the same time, the spread of the reported parameters across the measurement techniques is not constant: the greatest differentiation of Sa and Sq is observed for the 4-BAR surface, whereas for 2-BAR the differences are smaller. Overall, the results indicate that the structure/forming level (2/4/6-BAR) is the primary factor affecting Sa and Sq, while the measurement technique influences the obtained values in a systematic manner, with CL-1 consistently providing the highest readings for both parameters.

The relative error values for different surface texture parameters measured on isotropic sandblasted 7075 aluminium specimens at working pressures of 2, 4, and 6 bar are summarised in Table 2.

Table 2 Relative error δ_{Rel} values of selected surface topography parameters

	Symbol	Sq	Sa	Sku	Sk	Spk	Svk
		[%]	[%]	[%]	[%]	[%]	[%]
2-BAR	CL-1	6.8	6.9	-0.1	4.8	-18.5	18.9
	A20×	-6.2	-7.9	10.7	-9.4	-11.7	8.4
	WLI20×	4.1	4.2	-1.9	3.3	-18.5	11.2
4-BAR	CL-1	12.2	11.9	2.5	11.4	8.9	20.3
	A20×	4.1	3.4	6.3	2.6	2.4	12.0
	WLI20×	-13.1	-11.9	-11.3	-10.5	-23.3	-13.4
6-BAR	CL-1	11.2	10.6	0.8	9.2	6.9	19.8
	A20×	3.3	3.2	-0.5	2.4	0.9	5.5
	WLI20×	8.2	5.6	15.6	-1.8	7.5	32.5

For the 2-BAR specimens, measurements performed with the AltiSurf 520 profilometer (CL-1) show moderate relative errors for height parameters, with 6.8% for Sq and 6.9% for Sa, while peak and valley parameters exhibit larger deviations, particularly Spk (-18.5%) and Svk (18.9%). The focus variation microscopy device (A20x) tends to underestimate height parameters (Sq -6.2%, Sa -7.9%) but shows a positive relative error for Sku (10.7%). White-light interferometry results are closer to the reference for height parameters (Sq 4.1%, Sa 4.2%) but display significant deviations for Spk (-18.5%) and Svk (11.2%).

For the 4-BAR specimens, relative errors generally increase for CL-1, with Sq and Sa exceeding 12% (Sq = 12.2%, Sq = 11.9%), indicating higher sensitivity to surface roughness variations at increased sandblasting pressure. The Alicona µCMM provides smaller deviations, with Sq and Sa below 5%, and moderate overestimation of Sku (6.3%). WLI20x shows considerable underestimation across most parameters, particularly Sq (-13.1%), Sa (-11.9%), and Spk (-23.3%), suggesting challenges in accurately capturing surfaces with more pronounced textures.

For the 6-BAR specimens, the AltiSurf 520 profilometer continues to show high relative errors for height and valley parameters (Sq 11.2%, Svk 19.8%), while Alicona µCMM optical micro-measuring machine (A20x) again demonstrates better agreement with the reference, with Sq 3.3% and Svk 5.5%. The Optiv Reference 763 Dual Z (WLI20x) exhibits mixed performance, overestimating Sku (15.6%) and Svk (32.5%) while showing moderate errors for height parameters (Sq 8.2%, Sa 5.6%).

Overall, the analysis indicates that relative errors tend to increase with sandblasting pressure for all devices, reflecting the more complex surface textures at higher pressures. The non-contact AltiSurf 520 profilometer shows moderate errors for height parameters but larger deviations for peak and valley parameters. In comparison, the Alicona µCMM provides the most consistent results across all surface pressures, with generally low relative errors for Sq, Sa, and Svk. The white light interferometer, on the other hand, exhibits larger deviations, particularly for Spk and Svk, indicating potential limitations in capturing sharp peaks and deep valleys on strongly textured surfaces. These findings highlight the importance of careful device selection and the potential limitations of optical measurement methods when analyzing complex, sandblasted aluminium surfaces.

4. Conclusion

The conducted study enabled the evaluation of the accuracy of various non-contact surface topography measurement methods. The obtained results allow for the identification of the limitations of individual techniques and the determination of optimal methods for the analysis of complex surface structures. Based on the conducted research and analyses, the following conclusions were drawn:

- Optical methods reduce the influence of the profilometer tip, eliminating the need for morphological filtering.
- Relative measurement errors are primarily governed by the surface texturing process rather than the measurement technique.
- Proper selection of measurement parameters is essential to minimize non-measured points in non-contact measurements.
- Optical methods effectively capture general height parameters but may underrepresent sharp peaks and deep valleys on highly rough surfaces.

Future work will focus on:

- Quantifying the effect of filtering on selected topography parameters.
- Assessing the impact of measurement parameters on the occurrence of non-measured points.

References

[1] Salazar F, Barrientos A, 2013 Surface Roughness Measurement on a Wing Aircraft by Speckle Correlation *Sensors* **13**, 11772-11781

[2] Ramesh S, Karunamoorthy L, Palanikumar K, 2012 Measurement and analysis of surface roughness in turning of aerospace titanium alloy (gr5), *Measurement* **45**(5), 1266-1276

[3] Jakubowicz M, Gapiński B, Marciniak-Podsadna L, Mendak M, Mietliński P, Wieczorowski M 2023 Multiscale Evaluation of Jaw Geometry Reproduction Obtained Via the Use of Selected Orthodontic Materials in Dental Implants and Orthodontics—In Vitro Case Study *Appl. Sci.* **13**, 6932,

[4] Bartkowiak T, Peta K, Królczyk JB, Niesłony P, Bogdan-Chudy M, Przeszłowski Ł, Trych-Wildner A, Wojciechowska N, Królczyk GM, Wieczorowski M, 2025 Wetting properties of polymer additively manufactured surfaces – Multiscale and multi-technique study into the surface-measurement-function interactions, *Tribology International* **202**, 110394

[5] Nieslony P, Krolczyk GM, Krolczyk JB, Gupta MK, Bogdan-Chudy M, Grochalski K, Wojciechowski S, Wieczorowski M, Maruda RW, 2025 A novel use of non-contact methods in analyzing the physical and technical surface characteristics of different materials using electromagnetic measurement techniques *Measurement* **241**, 115672

[6] Grochalski, K, Mendak M, Jakubowicz M, Gapiński, B, Swojak N, Wieczorowski M, Krawczyk A 2021 Differences in Roughness Parameter Values from Skid and Skidless Contact Stylus Profilometers. *Advances in Science and Technology Research Journal* **15**(1), 58-70

[7] Koblar V, Filipič B, 2021 Evolutionary design of a system for online surface roughness measurements *Mathematics* **9**(16), 1904

[8] Rojewski M, Nowinka B, Czyżewski P 2024 3D Optical and Mechanical Roughness Measurements of Complex and Irregular Structures on the Basis of Polypropylene Moldings. *Advances in Science and Technology Research Journal* **18**(5), 245-257

[9] Duboust N, Ghadbeigi H, Pinna C, Ayvar-Soberanis S, Collis A, Scaife R, Kerrigan K 2016 An optical method for measuring surface roughness of machined carbon fibre-reinforced plastic composites. *Journal of Composite Materials* **51**(3), 289-302

[10] Pawlus, P.; Wieczorowski, M.; Mathia, T. *The Errors of Stylus Methods in Surface Topography Measurements*; Zapol: Szczecin, Poland, 2014.

[11] Leach, R. (Ed.). Optical Measurement of Surface Topography. Springer, 2013.

[12] Kiran MB 2021 A novel on-line surface roughness measuring method, Proceedings of the International Conference on Industrial Engineering and Operations Management, 2907 – 2916

[13] Joyce AM, Kane DM, Chater RJ 2006 Optical surface profilometry of low reflectance materials - Evaluation as a laser processing diagnostic, PICALO 2006 - 2nd Pacific International Conference on Applications of Laser and Optics - Conference Proceedings, 406-410

[14] Forgács I, Antal Á 2025 Comparison of Structured Light Projection-based Surface Reconstruction Methods, *Periodica Polytechnica Mechanical Engineering*, **69**(2), 151-163

[15] Zhao F, Tang H, Zou X, Li X 2025 A Review of Optical Metrology Techniques for Advanced Manufacturing Applications, *Micromachines* **16**(11), 1224

[16] Idicula MS, Mitura P, Józwik M, Choo H-G, Martinez-Carranza J, Wen K, Kozacki T 2022 Multi-incident holography profilometry for low and high gradient object Proceedings of SPIE - The International Society for Optical Engineering, 12138

[17] Petzing J, Coupland JM, Leach R 2010 The measurement of rough surface topography using coherence scanning interferometry. Measurement Good Practice Guide No. 116, National Physical Laboratory

[18] Newton L, Thanki A, Bermudez C, Artigas R, Thompson A, Haitjema H, Leach R. 2023 Optimisation of Imaging Confocal Microscopy for Topography Measurements of Metal Additive Surfaces. *Metrology* **3**(2) 186-221

[19] Mustafa A M, Muhamedsalih H, Tang D, Kumar P, Jiang J 2024 Chromatic focus variation microscopy for surface metrology *Opt. Express* **32**, 35527-35541

[20] Zhao F, Tang H, Zou X, Li X. 2025 A Review of Optical Metrology Techniques for Advanced Manufacturing Applications. *Micromachines* **16**(11), 1224

[21] Ma YD, Xiao YC, Wang QQ , Yao K, Wang XR, Zhou YP, Liu YC, Sun Y, Duan J 2025 Applications of Chromatic Confocal Technology in Precision Geometric Measurement of Workpieces Journal of Physics: Conference Series, 2460, International Symposium on Advanced Launch Technologies 2460 012077

[22] Gogolewski D, Kozior T, Zmarzły P. 2024 Multiscale Analysis of Surface Topography for Engineering Applications in the Casting Industry. *Materials* **17**(21):5272

[23] Weckenmann A, Jiang X, Sommer K-D, Neuschaefer-Rube U, Seewig J, Shaw L, Estler T, 2009 Multisensor data fusion in dimensional metrology, *CIRP Annals* **58**(2), 701-721

[24] Le Goïc G, Bigerelle M, Samper S, Favrelière H, Pillet M. 2016 Multiscale roughness analysis of engineering surfaces: A comparison of methods for the investigation of functional correlations *Mechanical Systems and Signal Processing* **66-67**, 437-457

[25] Macdonald DA, Martisius NL, Stemp WJ, Brown CA, Guthrie L, Gleason MA 2025 Quantification of microwear on experimental shell tools: First results using focus variation microscopy, surface roughness, and multiscale geometric analyses. *J Archaeol Sci Rep.* **62**,104986

[26] Wang A, Xie, B, Liu Z, 2017 Design of measurement system of 3D surface profile based on chromatic confocal technology," Proc. SPIE 10616, International Conference on Optical Instruments and Technology: Optical Systems and Modern Optoelectronic Instruments, 1061618

[27] Danzl R, Helmli F, Scherer S. 2011 Focus Variation – a Robust Technology for High Resolution Optical 3D Surface Metrology. *Strojniški vestnik - Journal of Mechanical Engineering*, **57**(3), 245-256

[28] ISO 25178-604:2025 Geometrical product specifications (GPS) — Surface texture: ArealPart 604: Design and characteristics of non-contact (coherence scanning interferometry) instruments