

Assessment of selected parameters of the geometric structure of the surface based on mechanical and electromagnetic mapping

Piotr Niesłony, Grzegorz Królczyk, Jalanta Królczyk, Marta Bogdan-Chudy, Roman Chudy

Politechnika Opolska, Wydział Mechaniczny

Karol Grochalski, Szymon Wojciechowski, Dominika Podbereska, Michał Wieczorowski

Politechnika Poznańska, Wydział Inżynierii Mechanicznej

Katarzyna Nicińska, Łukasz Ślusarski

Główny Urząd Miar, Laboratorium Precyzyjnych Pomiarów Geometrycznych

Corresponding author's e-mail address: p.nieslony@po.edu.pl

Abstract

The article analyses the problem of assessing the topography of mechanical and electromagnetic surfaces obtained by various contact and non-contact scanning techniques. The electromagnetic surface of the scanned topography was obtained using various scanning techniques and methods such as Confocal, Focus Variation and coherence scanning interferometry technique and Confocal Fusion method. To improve the correlation between mechanical and electromagnetic surfaces, morphological filters were used based on two basic operations: dilation and erosion. Additionally, for the coherence scanning interferometry technique, the quality of the topography of the scanned surface was assessed using two colours of light: green and white. It was found that the use of morphological filtration has little impact on changes in roughness parameters. It was observed that the best agreement between electromagnetic and mechanical surfaces was obtained when working with the interferometry technique.

Keywords: optical profilometer, non-contact measuring methods, topography analysis, scanning colours, morphological operations.

1. Introduction

Every process of shaping machine elements involves changing the geometric structure of the external surface. Achieving the appropriate functionality of this surface is one of the essential elements in the design of technological processes [3,6,16]. Engineers have known for many years a range of technologies that allow changes not only to the geometric structure of the surface but also processes that affect modifications of deeper material layers [4,9,17]. This layer is defined as the technological surface layer and often undergoes very rigorous evaluations [2,7,10-12,14], including destructive and non-destructive testing. Engineers carrying out technological processes, however, want to continuously assess the quality of the shaped technological surface layer without the need for significant interruption of the production process or even destruction of the produced

elements [8,13]. In this regard, the long-standing solution is the geometric evaluation of the external surface. For many years, there have been standards that detail methods for measuring the geometric structure of the surface using contact methods [23]. The introduction of new techniques and measurement methods has necessitated the introduction of standards in this area. The changing paradigm of measuring the geometric structure of the surface in recent times leads the manufacturing community to recognize non-contact measurements as reliable, resulting in surfaces described as electromagnetic, as opposed to mechanical surfaces that replicate the surface measured by contact instruments [15].

Microscopes used in industry for measuring surface topography are characterized by various measurement techniques and methods. These include Confocal, Focus Variation and coherence scanning interferometry techniques and the Confocal Fusion method. Each of these

techniques is based on scanning the surface with light of varying colors, often dependent on the manufacturer of the measuring device. Currently, there are no guidelines allowing for a clear comparison and assessment of the impact of measurement techniques and methods on the obtained values of surface roughness parameters or topography in relation to the same parameters acquired for mechanical surfaces. The article presents research in this area, additionally introducing an interesting development of digital filters {morphological filters [1,19-22]} aimed at aiding in obtaining correlations between mechanical and electromagnetic surfaces.

2. Experimental research

In this work one of the basic commercial materials such as Steel C45 has been used for machining tests. It belongs to the European standard EN 10083-2, the steel C45 is a medium carbon steel with good tensile strength and mechanical properties. The applications of Steel C45 span various industries due to its suitable characteristics. This steel is frequently used for manufacturing machinery components such as shafts, spindles, and durable elements of working machines. Wherever high stresses and wear resistance are crucial the C45 steel it suitable for applications as the first-choice material.

In addition, the research on the turning process was carried out on the Okuma Genos L200-EM multi-tasking CNC lathe machine. The CNC lathe is characterised by high static and dynamic stiffness, which is related to using a sliding solution for moving tool supports. The tool material used was coated carbide WC with (Ti, Al)N/ (Al, Ti)N. The technical specification of tool holder and cutting insert used are SVJBR 25x25-16 with VCMT 160404-PS AH6225, respectively. PVD-coated carbides involve a cemented carbide substrate with a Titanium compound (Ti, Al)N, coated to 1 to 3 μm thickness using the physical deposition (PVD) process after Tungaloy. Wear-resistant Ti(C, N, O) base coatings outperform TiN coatings. Conversely, a (Ti, Al)N base coat resists oxidation better. These grades can be interrupted cut due to their strong covering and substrate. Finish machining parameters were used for machining this steel. These parameters achieve good surface topography was it important to determine correctly roughness parameters for different measurement technics. Further, the machining parameters were kept fixed, i.e., $v_c=280$ m/min, $f=0.075$ mm/rev, $a_p=0.1$ mm.

In the turning process, a surface was obtained, whose geometric structure was evaluated using various measurement techniques. As part of the research, an assessment was made of the influence of the method of replicating the technological surface on its functional

parameters described by a set of roughness parameters. The studies were conducted using a contact profilometer and an optical topographic microscope.

The contact profilometer was a Hommel T8000 device with a TKU 300 measuring head and a measuring tip with a diamond cone angle of 90 degrees with a radius of 2 μm . The measurement parameters were as follows: the Z axis (vertical) range ± 80 μm . Measurement speed: 0.2 mm/s. The Sensofar S neox 090 equipment was used as a topographic optical microscope, which, as a multi-sensory equipment, allows for scanning surfaces using the Confocal, Focus Variation and coherence scanning interferometry technique and Confocal Fusion method.

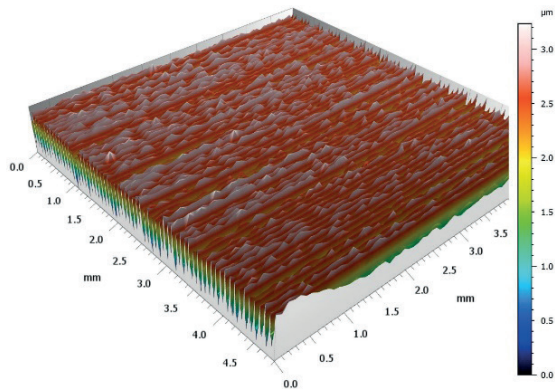
In the mechanical engineering, automotive, and aerospace industries, there still exists a paradigm that dictates using contact measurements for accurately assessing surface topography. However, with the development of the Industry 4.0 revolution, where continuous, unmanned control of the production process becomes a crucial production element, the use of fast scanning devices for the surface assessment using non-contact methods becomes a necessity. Understanding the differences in surface assessment using metrologically different measurement techniques is essential. According to the literature [15], when measuring surfaces using contact methods or profilometers, we obtain the so-called mechanical surface. Performing the same measurement using non-contact devices, such as optical or laser scanners/microscopes, mostly yields an electromagnetic surface (visible light lies within the electromagnetic spectrum). Additionally, the influence of non-contact measurement techniques and methods should be expected. Understanding their impact on the quality of the assessed geometric structure of the surface is of significant utilitarian importance.

Figure 1 presents an isometric view of both the mechanical and electromagnetic surfaces of the same sample.

Clear differences are visible in the presented isometric views between the mechanical and electromagnetic surfaces. Since the sample for the study was produced by turning, resulting in a characteristic anisotropic surface, it becomes possible to analyse the surface quality based on its roughness profile. Example visualizations of the mean profile generated in the MountainsMap Expert 10.0 system from 9 intermediate profiles are shown in Figure 2.

According to the requirements of the surface roughness profile determination procedure, S and L-type filtering were applied, and the measurement segment was set at 4.6 mm. A Gaussian filter with a value of 2.5 μm

a)



b)

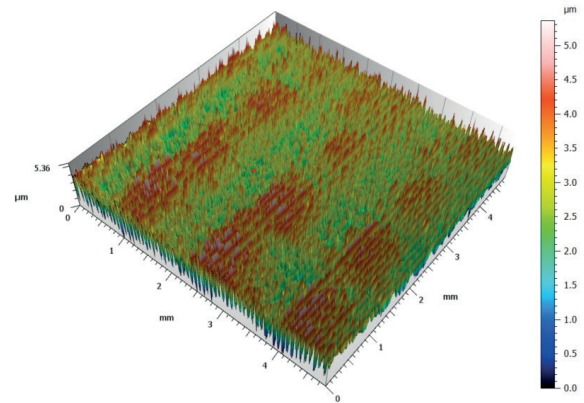


Fig. 1. Isometric view of the mechanical surface (a) and the electromagnetic surface (b) created by FV scanning.

was applied as the S filter (S-FILTER), which eliminates the smallest elements from the primary surface, and a Gaussian filter with a value of 0.8 mm was also applied as the L filter (L-FILTER), which eliminates the largest elements from the surface. The result of this filtration is defined as the S-L SURFACE.

Example profiles of the mechanical and electromagnetic surfaces, presented in Figure 2, already visually exhibit different natures of waveforms. In the case of the profile from the mechanical surface (Fig. 2a), a

relatively uniform waveform is visible, with fluctuations in the profile height ranging from $-1.0\ \mu\text{m}$ to $1.5\ \mu\text{m}$. For the electromagnetic surface, a sinusoidal profile is observed (Fig. 2b), with the range of profile height changes comparable to the profile obtained for contact measurements. To assess the influence of non-contact topography measurement techniques, additional profiles were extracted for one of the most accurate surface scanning methods – coherence scanning interferometry technique. In this case, a comparison of the scanning result

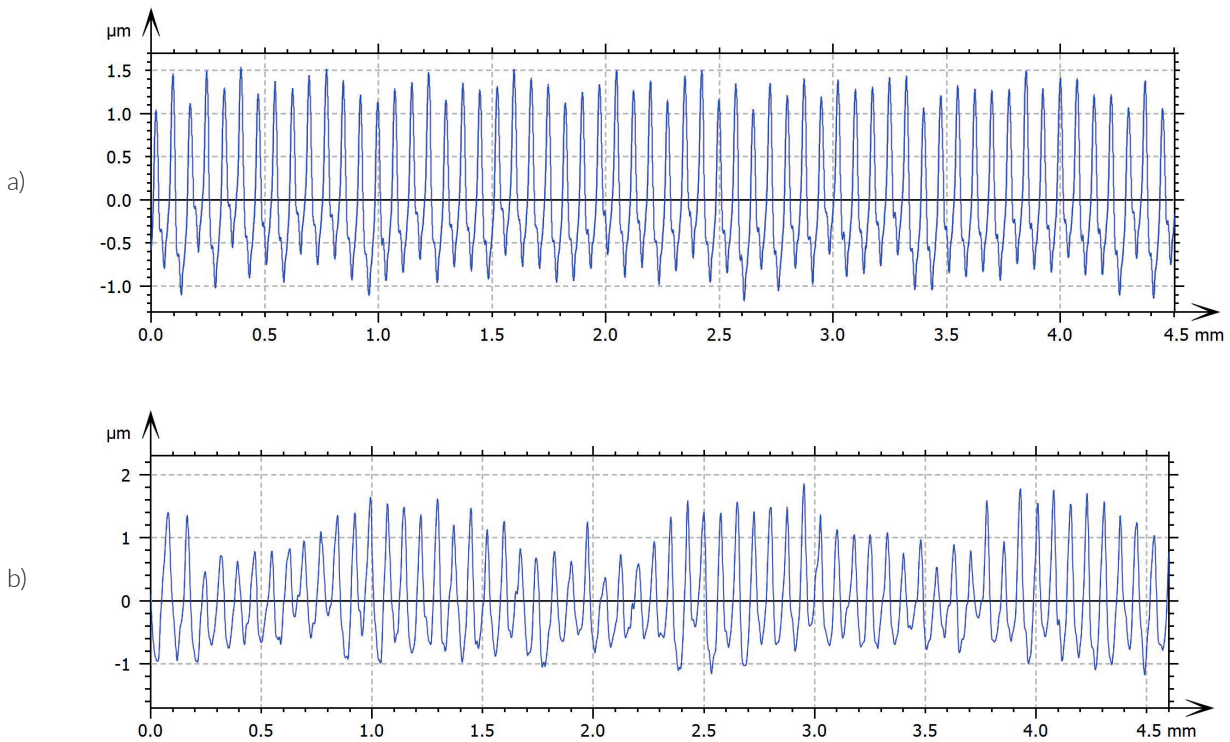


Fig. 2. Average profile from 9 profiles generated from the mechanical surface (a) and the electromagnetic surface (b) created by FV scanning.

was additionally made concerning the light color. In most optical topographic microscopes used for surface scanning, white or green light is employed. Changing the light color significantly affected the digital representation of surface topography. A comparison of two surface topographies obtained using the coherence scanning interferometry technique for the same (identical) surface fragment is presented in Figure 3.

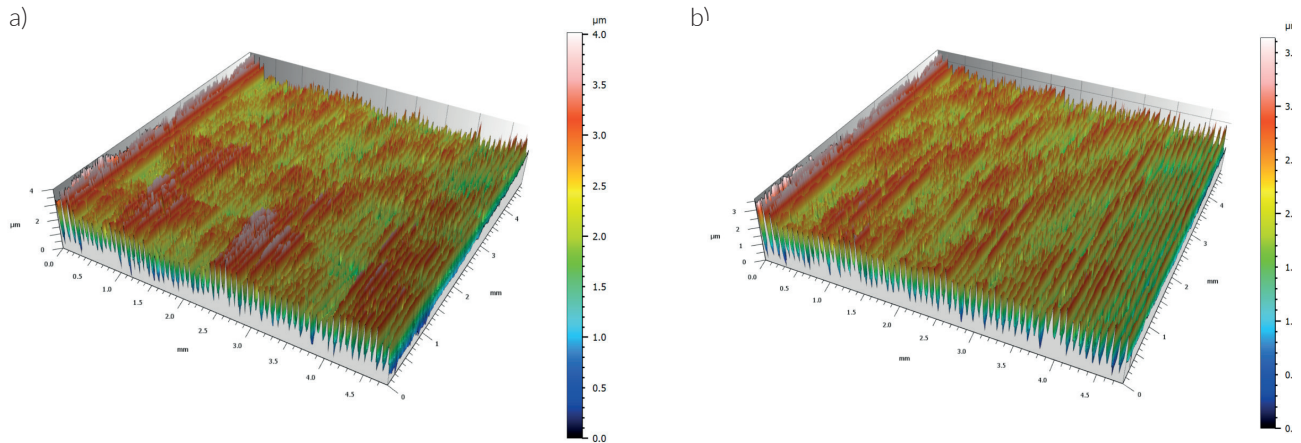


Fig. 3. Isometric view of the electromagnetic surface created by coherence scanning interferometry with green light (a) and white light (b).

Based solely on the isometric images of the surface, it is difficult to assess its morphology unequivocally. For this purpose, a range of functional parameters is utilized. Although their determination method is clearly defined in the standards [23], there is a lack of information regarding the influence of surface replication methods on their quality or variability. In the literature on the subject [14,15], in manufacturing industries and line with historical conditions, mechanical surfaces obtained through replication by contact profilometers are considered as reference or base surfaces. When attempting to compare the morphology of mechanical and electromagnetic surfaces, difficulties arise due to the inherent measurement technique discrepancies. As is known, contact profilometers have a stylus in the form of a cone with a rounding radius equal to 5 μm (industrial devices) or 2 μm (laboratory devices). In the case of optical profilometers, there is no such limitation, and the only limitation is the reflectivity of the surface or the refraction and reflection of light. To compare mechanical and electromagnetic surfaces, morphological filtration can be applied. When measuring surface texture with a stylus instrument, the stylus tip, a sphere with a radius of 2 μm , slides on the surface during the scan. The instrument records the position of the sphere's centre and delivers the profile curve. This profile is not the real surface but the result of a morphological dilation of the real surface by a sphere with a radius of 2 μm . To get closer to the real surface

in this case, the measured profile should be eroded by the same structuring element after the scan, in order to compensate the dilation effect of the mechanical contact [5]. That can be matched by using the morphological filter. A morphological filter is based on two morphological operations, dilation and erosion, that work using a structuring element of a given size. For example, the profile below is dilated by a disk of a certain radius.

The disk rolls over the surface and the path of its center is recorded (Fig. 4a - red line). Dilation tends to enlarge peaks and fill holes in. Structuring elements can be theoretically of any shape. If the disk is rolled below the surface, it is called erosion (Fig. 4b). General concepts of morphological filters are discussed in ISO 16610-40 and ISO 16610-80. When dilation is followed by erosion, it is called a morphological closing which is a morphological filter that creates the upper envelope. The disk is rolled below the dilation line. The envelope closes holes and pores while following the upper shapes of peaks and hills.

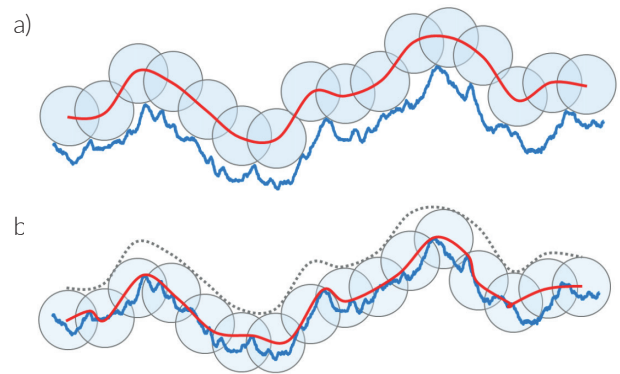


Fig. 4. Dilation (a) and erosion (b) as two basic morphological operations

If the sequence is reversed, i.e. erosion followed by dilation, it is called a morphological opening which creates the lower envelope. Morphological closing and morphological opening are filters but dilation and erosion they are just morphological operations [1,19-21].

Morphological filters are defined in ISO 16610-41 for profiles and in ISO 16610-81 for surfaces. They cover only the disc (sphere) and horizontal segment (planar) structuring elements, but in principle, one could use any shape as a structuring element. Alternating symmetrical filters are described in ISO 16610-49 for profiles and in ISO 16610-89 for surfaces [1,19-21].

To assess the effect of using morphological filtration, a digital image of the mechanical surface was generated using dilation and erosion filters. For each of the scanned surfaces (mechanical and electromagnetic), basic surface parameters were determined, such as:

- S_a , Arithmetical Mean Height,
- S_p , Maximum Peak Height,
- S_v , Maximum Pit Depth,
- S_z , Maximum Height.

and area roughness parameters:

- S_k , Core height
- S_{pk} , Reduced Peak Height
- S_{vk} , Reduced Valley Depth

The influence of measurement techniques and methods on the assessment of surface topography in terms of arithmetical mean height (S_a) is presented in Fig. 5. It was observed that the S_a parameter for the mechanical surface (with and without morphological filtration) gives approximately middle values in relation to S_a obtained from electromagnetic surfaces. The influence of morphological filters in this case is rather small. These filters contributed to a decrease in the S_a value, with the maximum difference, in relation to the mechanical surface without filtration, being only 1.8 %.

The smallest S_a values were obtained for interferometric measurements, regardless of the scanning light color (white light – primary color or green). In this case, $S_a=0.493 \mu\text{m}$ was obtained, which means a decrease in value in relation to the mechanical surface by as much as 16.7%. The use of Focus Variation, Confocal or Confocal Fusion led to an increase in S_a . The average increase in S_a is 16.2 %.

Evaluation of the geometric structure of the surface based on the S_a parameter takes into account the feature of averaging surface topographies resulting from the functionality of this parameter. The significant influence of measurement techniques was much more visible in the assessment of the geometric structure of the surface

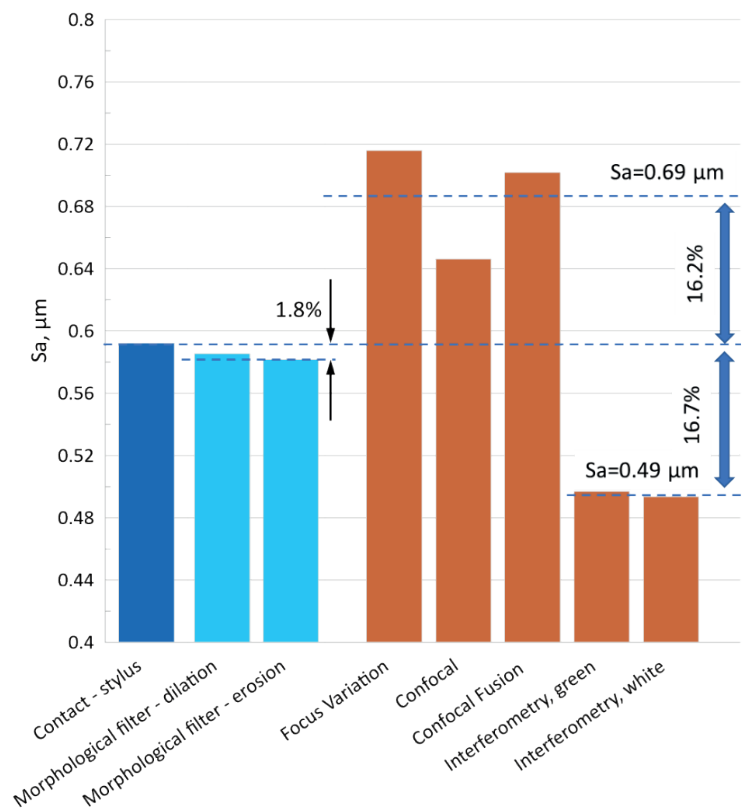


Fig. 5. Changes in the S_a parameter for different techniques and measurement methods, as well as the use of scanning light colors and morphological filters, are shown in Fig. 5.

using height parameters. The influence of measurement techniques and methods on changes in Sp , Sv , and Sz is presented in Fig. 6.

It was observed that the Sv parameter, determining the maximum pit height, is at a comparable level for the mechanical and electromagnetic surfaces obtained by interferometric scanning and Focus Variation technique. Significant decreases in Sp and Sv values were achieved after applying morphological filters. In relation to the mechanical surface, the average decrease for Sv and Sp was 34 %.

It should be emphasized that the applied morphological filter did not improve the agreement of the analysed parameters regarding the mechanical and electromagnetic surfaces. For the measurement techniques used, much better agreements were obtained without using this filter. For example, after interferometric scanning, the difference between the Sp of the mechanical surface and the electromagnetic surface obtained for green and white light was -7.8 % and -15.4 %, respectively. Comparing these data to the Sp and Sv parameters after filtration, a value of -22 % and more is obtained. It was observed that interferometric scanning resulted in a decrease in Sp and Sv values compared to the mechanical surface. Other techniques and methods for scanning

topographies (Focus Variation, Confocal Confocal Fusion) lead to an increase in Sp and Sv values. In this respect, only the Focus Variation technique gives acceptable values in relation to the mechanical surface.

Analyzing the resulting Sz parameter, which is defined as the sum of the largest peak height (Sp) value and the largest pit depth (Sv) value, a decrease in Sz for interferometry and an increase for the other scanning techniques were obtained. The smallest differences in relation to the mechanical surface were obtained for interferometric scanning with green light (-10.5 %) and Focus Variation technique (15 %).

An interesting analysis was the observation of the influence of measurement techniques and methods on functional parameters. In this regard, basic areal material ratio curve parameters such as Sk , Spk , and Svk were used (Fig. 7).

Based on the areal material ratio curve charts (examples in Fig. 7), significant changes in the course of these curves depending on the measurement techniques and methods were observed. For this reason, an analysis of the curves was conducted through the parametric evaluation of their main features described by the values of Sk , Spk , and Svk (Fig. 8).

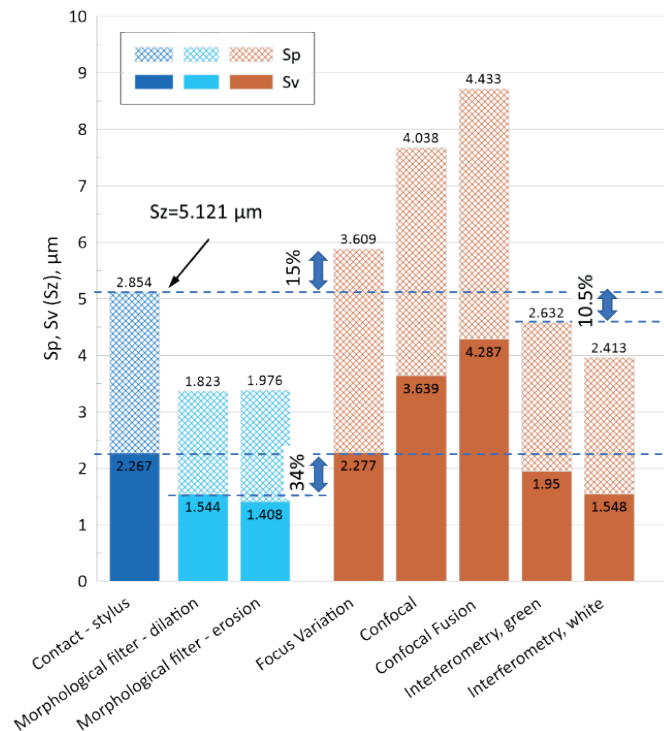


Fig. 6. Changes in the Sp , Sv , and Sz parameters for different techniques and measurement methods, as well as the use of scanning light colors and morphological filters.

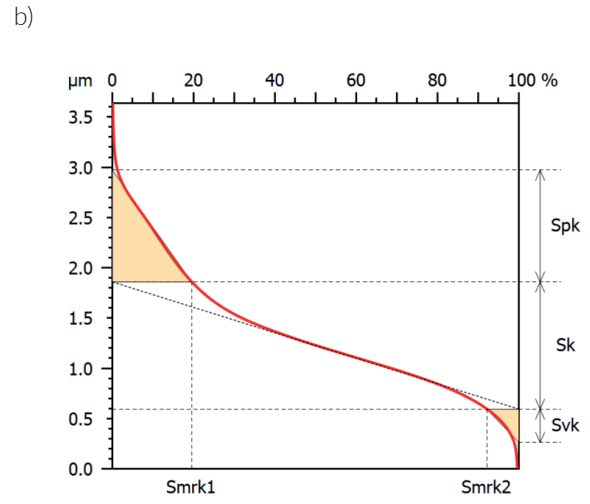
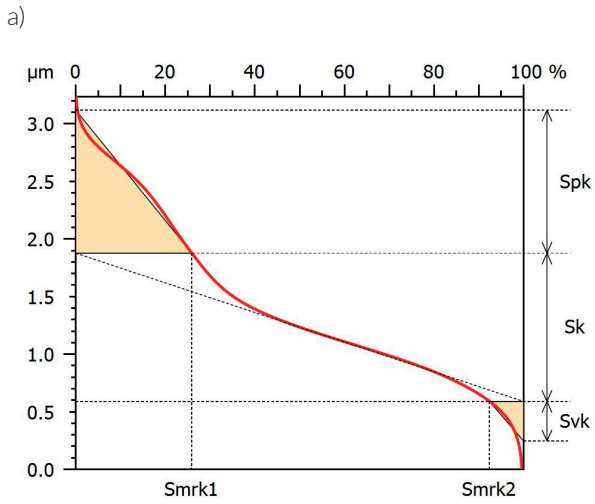


Fig. 7. Areal material ratio curve for mechanical surface (a) and electromagnetic surface created by interferometric scanning using white light.

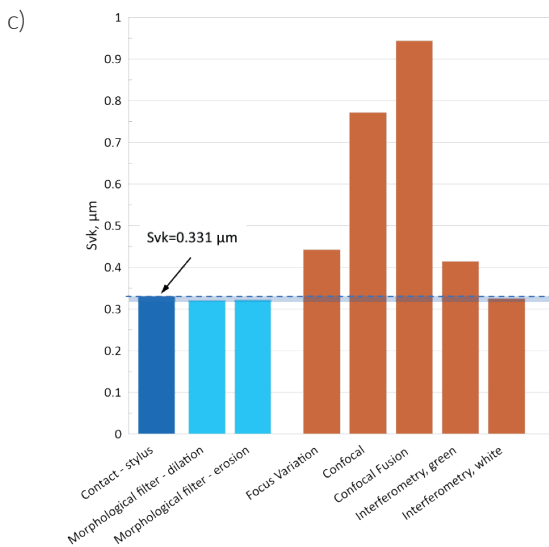
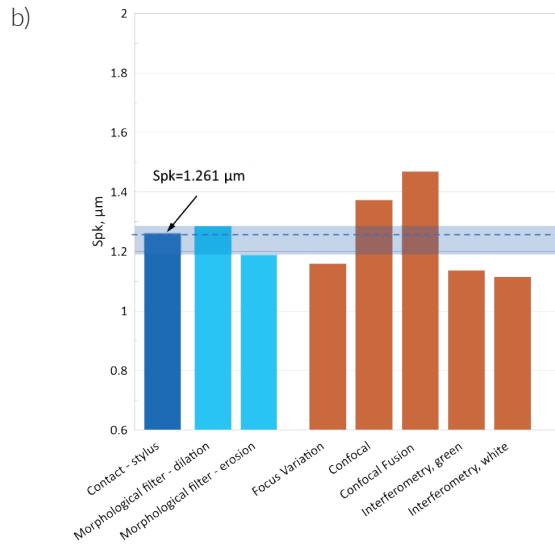
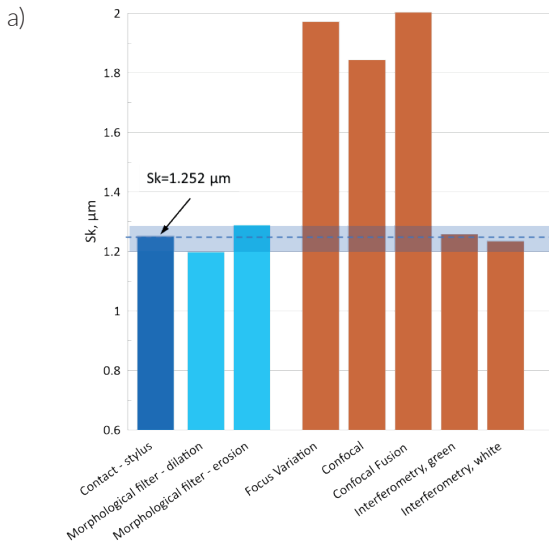


Fig. 8. Changes in the SK , Spk , and Svk parameters for different techniques and measurement methods, as well as the use of scanning light colors and morphological filters.

The morphological filter significantly affects the value of the core height Sk and the reduced peak height Spk . Interestingly, depending on the type of filter (dilation or erosion), the Sk and Spk parameters are sometimes larger and sometimes smaller than the nominal value, i.e., without the filter application (Fig. 8a and b). Generally, the morphological filter does not significantly affect the Svk parameter - reduced valley depth (Fig. 8c). It was observed that, from a technical point of view, the core height parameter achieves comparable values for mechanical and electromagnetic surfaces only after interferometric scanning (Fig. 8a). Other non-contact techniques generate values almost twice as high. This characteristic of these measurement techniques may lead to erroneous engineering interpretation of tribological or technological properties of the generated surface. It seems that this fact should be considered in the measurement methodology, for example, by correcting these values using a formula that considers the influence of the measurement technique.

The machinery industry expects the ability to assess the geometric structure of the surface based on profile parameters. This is mainly related to contact measurement techniques, where the use of simple, mobile contact devices allows for roughness evaluation directly at the point of manufacture. However, this solution must correlate with measurements already performed in

metrology rooms, on specialized contact and non-contact devices. For this reason, an assessment of changes in basic profile roughness parameters obtained by various measurement techniques and methods was made.

The morphological filter does not significantly affect the Ra parameter values (Fig. 9). The decrease in Ra obtained after filtration falls within the range of standard deviation values determined for a series of 9 profiles. Interestingly, when evaluating Ra in relation to contact measurements, the greatest differences were obtained for profiles from interferometric scanning. Evaluating only their average values, a decrease in Ra of up to 20 % was obtained in this case - Fig. 9.

The best agreement of the electromagnetic profile with the mechanical profile was obtained by the confocal method. Other non-contact methods generated Ra values about 7-8.8 % higher. However, it should be noted that the Ra parameter shows low stability values for a series of profiles (9 profiles) generated from the baseline electromagnetic surface. The standard deviation for these profiles falls within the range of 0.04-0.07 μm , which represents a spread of 8-13 % from the contact Ra . Only good profile stability was achieved for interferometric scanning with white (baseline) light, where the spread determined by the standard deviation is comparable to contact measurements and falls within the 2 % limit.

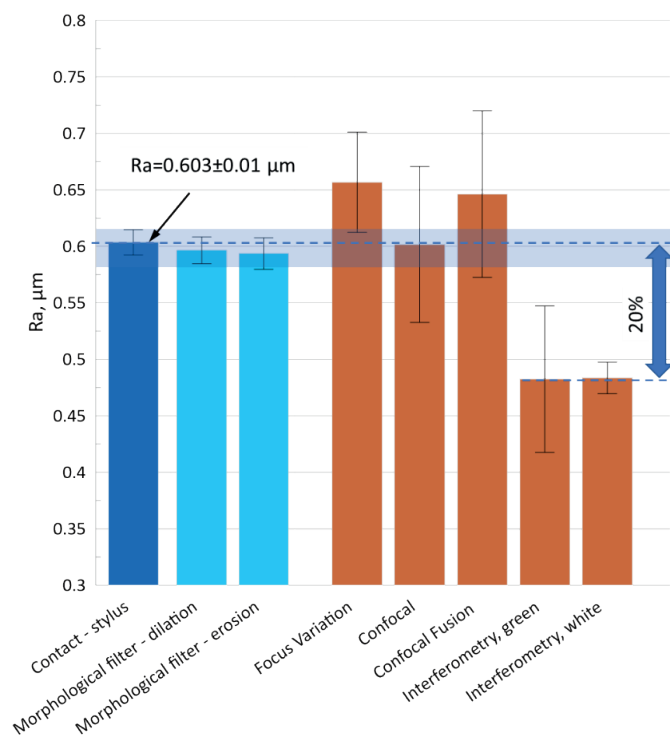


Fig. 9. Changes in the roughness parameter Ra for different techniques and measurement methods, as well as the use of scanning light colors and morphological filters.

Interesting changes were observed during the analysis of the height parameters of roughness profiles. Unlike the R_a case (Fig. 9), the best agreement was achieved for the electromagnetic profile based on interferometric scanning. In this case, the parameter R_p , relating to the maximum profile peak height, showed very good agreement between contact R_v and after interferometric scanning (Fig. 10). In the same context, R_v for interferometry showed a decrease in value of only 10%. Additionally, the obtained total R_z has good agreement with contact R_z . In this case, it can be indicated that roughness parameters R_p , R_v , and R_z determined from the profile obtained by interferometric scanning achieved acceptable agreement with parameters determined from the mechanical profile. Unfortunately, subsequent non-contact techniques do not perform well as techniques corresponding to contact methods. Based on profiles obtained by Focus variation, Confocal or Confocal Fusion technique, higher values of parameters R_p , R_v , and R_z are always obtained compared to contact ones. The distribution of these changes correlates closely with the corresponding surface topography parameters (Fig. 6), where the still interesting measurement method combining confocal technique with Focus variation (Confocal Fusion), where the highest values of this set of roughness parameters reach almost 2 times the differences in relation to the baseline – contact profile.

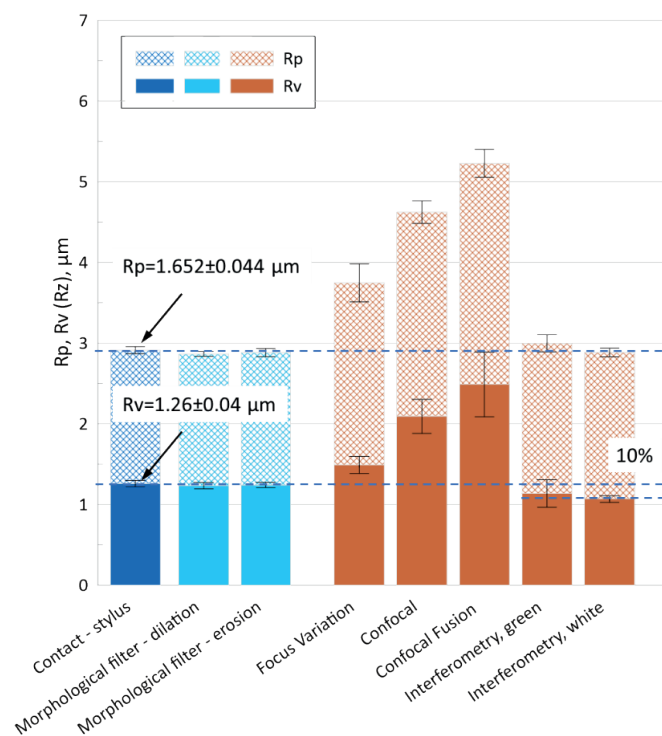


Fig. 10. Changes in the R_p , R_v , and R_z parameters for different techniques and measurement methods, as well as the use of scanning light colors and morphological filters.

3. Conclusions

Based on the conducted research, significant influence of measurement techniques and methods on the values of surface topography and roughness parameters was observed. The impact of digital correction methods of surface topography performed by morphological filtration was also analyzed. It was found that:

- The use of morphological filtration has little impact on changes in areal average roughness (Sa) or arithmetical mean height of the roughness profile (Ra). This filter significantly affected geometric height parameters such as Sp , Sv , Sz evaluated for surfaces. The influence of morphological filtration on the roughness profile is minor.
- For the group of arithmetical mean height parameters (Sa , Ra), no adequate measurement technique for electromagnetic surfaces was found that would allow achieving comparable parameters to mechanical surfaces. In this regard, coherence scanning interferometry technique always gives the smallest values for parameters Sa or Ra , regardless of the scanning light used.
- The best agreement between electromagnetic and mechanical surfaces was obtained when evaluating height parameters of the surface as well as the profile for coherence scanning interferometry technique. In this case, differences in the values of roughness profile parameters (Rp , Rv , Rz) did not exceed 10 %, and comparable deviations were also obtained for surface parameters after interferometric scanning with green light.
- Examining the effects of surface representation by various measurement techniques and methods in terms of areal material ratio, it was found that comparable values of Sk , Spk , and Svk for mechanical surfaces were obtained within a certain range for coherence scanning interferometry technique. Interestingly, in this case, the values of mean height of peaks above the core surface (Spk) for both mechanical and electromagnetic surfaces are comparable and show the smallest deviations from each other. Values of core roughness depth parameter (Sk) and reduced dale height parameter (Svk) are strongly dependent on the measurement technique. Also, in this case, Confocal, Focus Variation, and Confocal Fusion generate surface topography parameters significantly higher than those for mechanical surfaces.
- It should be noted that, fundamentally, optical scanning techniques such as Confocal, Focus Variation, and Confocal Fusion generate surface topography

parameters significantly higher than those for mechanical surfaces. This fact should be taken into account in measurement procedure algorithms where the comparison of surfaces obtained by different measurement techniques is foreseen.

ACKNOWLEDGEMENT

Scientific work/Publication co-financed from the state budget under the program of the Ministry of Science called „Polska Metrologia” (Polish Metrology) project number PM/SP/0054/2021/1 titled: "Functional Surface Analysis in Mechanical Engineering", grant amount 999 900.00 PLN, the total value of the project 999 900.00 PLN, Poland.



References

- [1] Blateyron F.: Good practices for the use of areal filters, Conference Paper Digital Surf, May 2014, DOI: 10.13140/2.1.10079361.
- [2] Broekel T.: Measuring Technological Complexity- Current Approaches and a New Measure of Structural Complexity, 2017, arXiv preprint arXiv:1708.07357, <https://arxiv.org/pdf/1708.07357.pdf>
- [3] Bruzzone A.A.G., Costa H.L., Lonardo P.M., Lucca D.A.: Advances in engineered surfaces for functional performance, CIRP Annals - Manufacturing Technology 57 (2008) 750–769.
- [4] Cheng, Y., Wang, Y., Lin, J. et al. Research status of the influence of machining processes and surface modification technology on the surface integrity of bearing steel materials. Int J Adv Manuf Technol 125, 2897–2923 (2023). <https://doi.org/10.1007/s00170-023-10960-x>
- [5] DIGITAL SURF - MountainsMap User Manual <https://guide.digitalsurf.com/en/guide.html> 19.
- [6] Gadelmawla ES, Koura MM, Maksoud TMA, Elewa IM, Soliman HH. Roughness parameters. J Mater Process Technol 2002;123(1):133–45. [https://doi.org/10.1016/S0924-0136\(02\)00060-2](https://doi.org/10.1016/S0924-0136(02)00060-2)
- [7] Krolczyk G.M., Maruda R.W., Krolczyk J.B., Nieslony P., Wojciechowski S., Legutko S., Parametric and nonparametric description of the surface topography in the dry and MQCL cutting conditions, Measurement 121 (2018) 225–239.
- [8] Maruda R. W., Wojciechowski S., Szczotkarz N., Legutko S., Mia M., Gupta M. K., Nieslony P., Krolczyk G. M., Metrological analysis of surface quality aspects in minimum quantity cooling lubrication. Measurement, (2021), vol. 171, s. 108847-1-108847-12.
- [9] Mu YZ, He TT, Shao RN, Zheng XM, Cui T, Du SM, Zhang YZ (2021) Effect of quenching holding time properties of on micro-structure and friction and wear GCr15 bearing steel. Trans Mater Heat Treat 42:109–116. <https://doi.org/10.13289/j.issn.1009-6264.2021-0253>
- [10] Niemczewska-Wójcik M., Wójcik A., The machining process and multi-sensor measurements of the friction components of total hip joint prosthesis, Measurement 116 (2018) 56–67.
- [11] Niemczewska-Wójcik M., Wójcik A: The multi-scale analysis of ceramic surface topography created in abrasive machining process, Measurement, Vol. 166, 2020, ISSN 0263-2241, <https://doi.org/10.1016/j.measurement.2020.108217>
- [12] Nieslony P., Cichosz P., Krolczyk G.M., Legutko S., Smyczek D., Kolodziej M., Experimental studies of the cutting force and surface morphology of explosively clad Ti–steel plates. Measurement., 78 (2016), pp. 129-137, 10.1016/j.measurement.2015.10.005.
- [13] Nieslony P., Krolczyk G.M., Wojciechowski S., Chudy R., Zak K., Maruda R.W., Surface quality and topographic inspection of variable compliance part after precise turning. Applied Surface Science Volume 434, 15 March 2018, Pages 91-101.
- [14] Nieslony P., Krolczyk G.M., Zak K., Maruda R.W., Legutko S., Comparative assessment of the mechanical and electromagnetic surfaces of explosively clad Ti–steel plates after drilling proces, Precis. Eng. 47 (2017) 104–110.
- [15] Pawlus P., Reizer R., Wieczorowski M., Krolczyk G.M., Sensitivities of surface texture parameters to measurement errors – A review, Measurement, Volume 227, 2024, ISSN 0263-2241, <https://doi.org/10.1016/j.measurement.2024.114323>
- [16] Serope K., Schmid S.: Manufacturing Engineering and Technology in SI Units, Pearson Education, 2022, 1312pp.
- [17] Thiele J.D., Melkote S.N., Peascoe R.A., Watkins T.R. (2000) Effect of cutting edge geometry and workpiece hardness on surface residual stresses in finish hard turning of AISI 2100 steel. J Manuf Sci Eng 122:642–649.
- [18] Youssef, Helmi A.; El-Hofy, Hassan A.; Ahmed, Mahmoud H.: Manufacturing Technology, Pevná, 2023, ISBN: 9781032432489, 920 pp.
- [19] ISO 16610-40: GPS – Filtration – Morphological profile filters: Basic concepts.
- [20] ISO 16610-41: GPS – Filtration – Morphological profile filters: Disk and line segment filters.
- [21] ISO 16610-80: GPS – Filtration – Morphological areal filters: Basic concepts.
- [22] ISO 16610-81: GPS – Filtration – Morphological areal filters: Sphere and planar segment filters.
- [23] ISO 25178: Geometrical Product Specifications (GPS), collection of international standards relating to the analysis of 3D areal surface texture.

