

## Procedure for data preparation for the correct evaluation of the geometrical structure of the surface in functional analysis

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### Abstract

Parametric results describing the geometric structure of a surface are influenced by many factors. One of the most important is the correct preparation of input data. This is related to the type of surface levelling, the selection of a suitable measuring section or the applied filtration. The data preparation procedure depends on the adopted measurement technique: contact or optical. Depending on the type of data acquisition, it is necessary to implement supplementary procedures. Each of the applied operations on data directly influences the obtained values of individual spatial parameters 3D and surface parameters 2D, such as roughness, waviness or base profile. In this paper, different surface levelling options and selected filtering methods were analysed. In the case of optical measurements, the influence of filling in non-measured points was also considered. The results obtained allowed us to develop of a data preparation procedure and to determine the influence of the different steps on representative parametric values.

It was found that the most significant factor influencing the parameter values obtained is the removal of outliers. In this study, based on two measurement techniques: contact and optical, a procedure for sequential processing of input data was prepared to assess the impact of the steps performed on the resulting values of parameters describing the surface structure. The procedure is based on one of two main types of surface levelling: levelling with the least squares plane (LS) and levelling line by line (LbL), along with the impact of one filtering method – removal of outliers (RO). In the case of optical measurements, the impact of filling unmeasured points (NM) was also considered. It was found that the most significant factor affecting the obtained parameter values is the removal of outliers (RO). The relative differences between the data for which this operation was not applied are 13 % for contact profilometry and approximately 1% for optical profilometry. On the other hand, the procedure of filling unmeasured points (NM) has the least impact – however, this is only applicable in the case of optical measurement techniques. The choice of the appropriate levelling method can affect the final results. Differences between these methods are generally small (up to 5 %), but in certain situations, they can be significant. The obtained results allowed for the development of a data preparation procedure and determining the impact of various stages on the representative parametric values.

**Keywords:** preparation of measurement data, levelling method, filtering, fill non-measured points (NM), texture analysis, contact profilometer, measure tip, optical profilometer, data acquisition,

## 1. Introduction

The evaluation of the surface texture is essential in terms of reliable characterization of product's quality and its operational/tribological properties [1]. Generally, there are many different surface texture measurement techniques. Concerning the way to obtain the surface texture information, these techniques can be divided into two categories: contact and non-contact [2–5]. Currently, the stylus profile meter is being the most widely applied contact method in the mechanical technology. In this process, a stylus moves across a surface and its vertical deviations are being acquired. Nevertheless, because of its low measurement efficiency, high fragility, risk of surface damage, and inability to measure online, stylus profile meters were unable to meet the needs of current automation industry [6, 7]. In order to eliminate the disadvantages of contact method, many non-contact methods have been developed by a scientists, including mainly the acoustics-based and optics-based techniques. Unfortunately, the acoustic methods are mainly applicable to products with large surface roughness, and thus their application is limited. An alternative to acoustic methods constitutes the optical measurement methods, which recently are being more widely applied in mechanical engineering. These methods include chromatic confocal microscopy, point autofocus instruments, focus variation instruments, phase shifting interferometry, coherence scanning interferometry and digital holographic microscopy [8, 9].

According to Królczyk et al. [10], the in-depth characterization of surface texture should be made both with application of parametric and non-parametric description. In available standards, parameters characterizing the surface roughness are described in groups. The group of parameters connected with the area is divided into the following sub-groups: height ones, frequency ones, hybrid ones, functions and related parameters and others. It should be noted that in relation to manufacturing technologies, the parametric characterization of surface texture is usually being made in accordance with the ISO 25178 standard and involves the evaluation of spatial surface roughness parameters (e.g.,  $S_a$  – average surface roughness,  $S_p$  – maximum peak height,  $S_q$  – root mean square surface roughness,  $S_z$  – maximum height of surface roughness, etc.). Niesfony et al. [11] investigated the 3D spatial surface roughness parameters during turning of the mould parts with variable compliance. The research revealed that the surface topography, alongside the 3D functional parameters influence the performance of the machined surface. Maruda et al. [12] studied the surface integrity during turning of AISI 1045 steel with various cooling/

lubricating techniques such as: machining in dry conditions, MQCL method, MQCL method with extreme pressure/anti-wear additive (EP/AW). The obtained results have shown that during turning with MQCL + EP/AW cooling, the surfaces with more even distribution of valleys and peaks were generated, which resulted, inter alia, in the reduction of selected spatial surface roughness height parameters ( $S_a$ ,  $S_p$ ,  $S_v$ ).

Reaching the desired surface quality is very important for maintaining the functional features of machine parts [13–15]. Thus, the surface texture should be also evaluated in terms of non-parametric analysis. The non-parametric analysis involves the assessment of the collected 3D points of the surface and their presentation in the form of contour maps and isometric images created in axonometric view. This kind of analysis enables the identification and analysis of surface formation mechanisms during the manufacturing processes. In example, the analysis of a 3D machined surface topographies enables identification of ploughing mechanisms during ball end milling [16], identification of chatter and feed marks during milling with slender and rigid tools [17], as well as chipping of hard SiC particles during laser assisted turning of metal matrix composites [18].

The above deliberations demonstrate that evaluation of surface texture is essential in manufacturing technology, however its accurate identification is strictly correlated with the selected input measurement settings, as well as the quality of measurement data preparation. The first and essential factor is the appropriate selection of the elemental and measurement lengths – according to the PN-EN ISO 4287:1999 and PN-EN ISO 11562:1998 standards. Moreover, the recent literature focuses also on other important aspects related to measurement data preparation and novel trends in measurement techniques. Lu et al. [19] conducted Electromagnetic Wave Scattering Simulation applied for the evaluation of surface roughness measurement accuracy. In a simulation procedure, authors included the variable light incident angles, the light wavelengths and various workpiece materials (stainless steel, copper, aluminum, and silicon carbide). The simulation results show that, when lower values of the average surface roughness height are obtained, the performance of low light incident angles is better than that of large ones. However, in case of higher tested average surface roughness height values, larger light incident angles are better, which derives to obtain better measurement accuracy. Li et al. [20] proposed a multifeature fusion model for the surface roughness of cold-rolled strip steel to improve the measurement efficiency of existing speckle methods. Experimental results confirm that the proposed multifeature fusion

model predicts surface roughness with a minimum mean square error of 0.237 %. Al-Kindi and Shirinzadeh [21] developed a method for using machine vision data to acquire reliable surface roughness parameter measurement. Authors compared the stylus-based with vision-based measurements using standard and non-standard surface roughness parameters. Two light reflection models namely Intensity-Topography Compatible (ITC) model and Light-Diffuse model were adapted and applied to interpret acquired vision data and to enable suitable computation of surface roughness parameters. Results showed that the ITC model gives more superior results compared to the Light-Diffuse model with remarkable close values to those acquired by the traditional stylus-based data for a majority of surface roughness parameters. Zhang et al. [22] proposed a simulated data and transfer kernel learning-based visual surface roughness measurement method. The experimental results demonstrated that the developed method can achieve an accuracy of over 90 % based on the simulated data and transfer kernel learning, therefore providing a new improvement strategy for visual surface roughness measurement. Weckenmann and Krämer [23] conducted a study concerned with the determination of the task-specific measurement uncertainty for computer tomography (CT) measurements as it is an important parameter describing the quality and the reliability of measurement results. The work has been focused on the determination of influences which can be controlled by the machine operator in the preparation of the measurement data acquisition and evaluation, like the magnification of the workpiece, the number of projections taken, or the position and orientation of the workpiece. Authors have confirmed that these factors have influential effect on the CT measurement uncertainty.

The next influential aspect concerning the reliability of GPS measurements is the applied signal filtering method. A filtering process is the most complicated and least characterized phase of information processing in surface metrology. According to Whitehouse [24], the filtration is a method for decomposition of profile components with different wavelengths. Currently there are many methods employed for a surface roughness signal filtering. Among these methods, mainly the Gaussian filtering [25, 26], spline filtering [27, 28] and wavelet transform filtering methods [29, 30] are widely presented in a literature. Barrios-Muriel et al. [31] developed the Singular Spectrum Analysis (SSA) filtration technique for a surface roughness measurement. The results confirm that when selecting an adequate window length, the SSA technique is an interesting alternative to the standardized methods such as Gaussian filter, Splines and Wavelets.

The obtained Results demonstrate high robustness to outliers and dropouts that are produced in the real surface roughness measurements. Zakharov et al. [32] presented the generalized analysis of various types of an asymmetric morphological filter based on simulation. It has been demonstrated that the asymmetric morphological filter is effective for scale space analysis of surfaces with significant shape errors and waviness. Thus, the obtained results can be applied to evaluate the tribological properties of multifunctional surfaces of products.

The above deliberations reveal that problems of reliable surface texture evaluation in manufacturing technologies constitute the topical problem. Nevertheless, the aspects related to appropriate selection of input measurement settings, as well as the quality of measurement data preparation are still insufficiently investigated. Thus, this work fills this research gap and focuses on the procedure for preparing input data for the reliable assessment of the geometrical product specification.

## 2. Methodology

### 2.1. Materials and devices

As it already was mentioned in the introduction, the development of manufacturing processes for machine and equipment components is closely linked to the improvement of inspection methods and the determination of functional surface characteristics. In this study, two measurement techniques were used: contact and optical.

The surface structure analysis was performed using the contact method, using a Hommel T8000 device with a TKU 300 measuring head and a measuring tip with a diamond cone angle of 90 degrees. The measurement parameters were as follows: the Z axis (vertical) range  $\pm 80 \mu\text{m}$ , the measured area  $4.8 \times 4.8 \text{ mm}$ . Gauss filtering at  $0.8 \mu\text{m}$ , 480 profiles were measured. The filtration parameters were applied according to the recommendations of ISO 16610.

The optical measurement was carried out using a Sensofar S neox optical profilometer. Its measurement resolution in the direction of Z-axis is 2 nm. The instrument is characterized by repeatability of 0.1 % and accuracy of up to 0.5 %. In addition, the optical profilometer used offers several measurement modes:

- Phase Shift Interferometry (PSI) has been developed to measure the surface height of very smooth and continuous surfaces with sub-Angstrom resolution, for all numerical apertures (NA). Very low magnifications (2.5×) can be employed to measure large fields of view with the same height resolution.

- Coherence Scanning Interferometry (CSI) uses white light to scan the surface height of smooth to moderately rough surfaces, achieving 1 nm height resolution at any magnification.
- Extended Phase Shifting Interferometry (ePSI) combines two interferometric technologies, CSI and PSI, overcoming the limitations of the two by achieving 0.1 nm of measurement noise in a larger range of some hundreds of microns.
- VSI White-light vertical scanning interferometers.

The research issue presented here uses data recorded using the VSI method. The influence of the other measurement modes on the results obtained is a separate research aspect.

For both contact and optical measurements, the same set of specimens and identical, precisely defined measuring areas were used. The measuring field was defined at  $4.8 \times 4.8$  [mm].

The test objects were specially prepared surfaces. They were made of different types of materials and using different surface shaping techniques. The materials were selected in terms of function and industrial applicability. A catalogue of the tested specimens is presented in Table 1.

The surfaces of the specimens were each finished by precision machining in such a way that they were parallel to each other and bore no traces of previous technological operations, particularly milling. This procedure was

Tab. 1 Materials and their selected characteristics used to make the testing specimen

MATERIAL	APPLICATION
Stainless steel (304)	This grade is resistant to most oxidising acids and can withstand ordinary rusting. It is resistant to foodstuffs, sterilisation solutions, most organic chemicals and dyes and a wide range of nonorganic chemicals. It is used frequently in the food industry.
Carbon steel (C45)	Carbon steel, also known as higher quality unalloyed steel. It is used for manufacturing of machine parts because of its properties. It is easily machined.
Aluminium (2017A)	This alloy has good strength properties (tensile strength, high fatigue strength) and is well suited for machining. It is moderately resistant to corrosion. It can be subjected to welding. It is used for components in the automotive industry, machine parts and aircraft structural components.
Aluminium (7075)	An aluminium alloy with very high mechanical strength and high fatigue resistance. It has medium corrosion resistance and is suitable for machining, polishing and grinding. It is used in moulds for foam plastics, stamping and punching parts, in heavy-duty machine and structural components as well as in aerospace and sports equipment components.
Copper (M1E)	It is characterised by very good electrical conductivity. It is suitable for enamelling and refining annealing. It is used for electrical discharge machining and in the electrical industry, in electrical installations, in the manufacture of apparatus for the chemical and food industries, for radiators, printed circuits and electrical machine parts.
Brass (MO58A)	This alloy is used in the manufacture of industrial and marine fittings, clamps, piping and plumbing. An advantage of the alloy is its good susceptibility to hot forming. These properties make it easy to obtain any shape, even very complex ones. Brass elements can be easily machined.

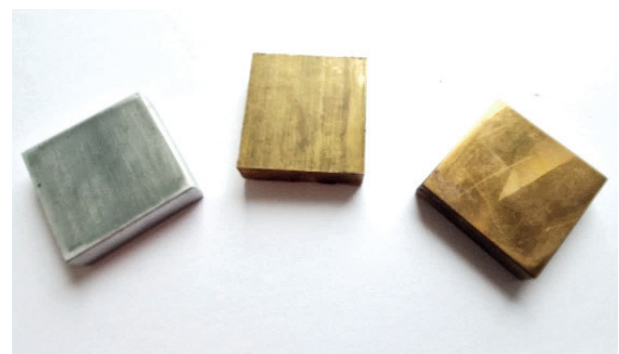
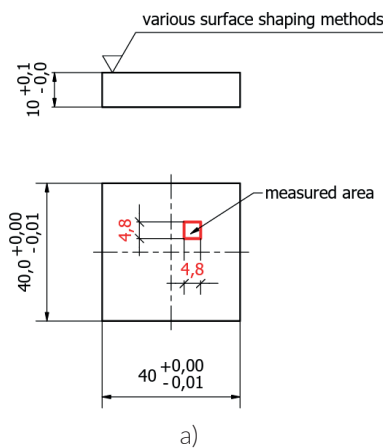


Fig. 1. Specimens made for testing with a specially shaped surface a) engineering drawing; b) view of samples and their surfaces

intended to reduce as far as possible interference that could affect the extraction and identification of characteristic traits. The objects prepared in such a way were then subjected to a specialised surface shaping process. Selected, measured specimens are shown in Fig 1.

Surface texturing was carried out using selected processing techniques that are most commonly used in industrial applications. The following surface texturing methods were listed for each of the materials used:

- Glass bead blasting – operating pressure 2; 4; 6 [bar],
- Blasting – operating pressure 2; 4; 6 [bar],
- Whetting – 12; 21; 30 [kHz],

The surface textures thus prepared were then measured using contact and optical techniques. The data obtained were further analysed.

## 2.2. Calculation procedure

The structures prepared by the various surface shaping techniques regardless of the data acquisition method were saved as .sur files. The geometric surface structure analysis was carried out in MountainsMap 10 software.

A procedure was prepared in the software to deal with the input data in a sequential manner. This was to assess the impact of each step on the result obtained. The values of the parameters describing the surface structure each time provided a feedback value for the data operation carried out. The procedure is shown in the form of a diagram (fig. 2).

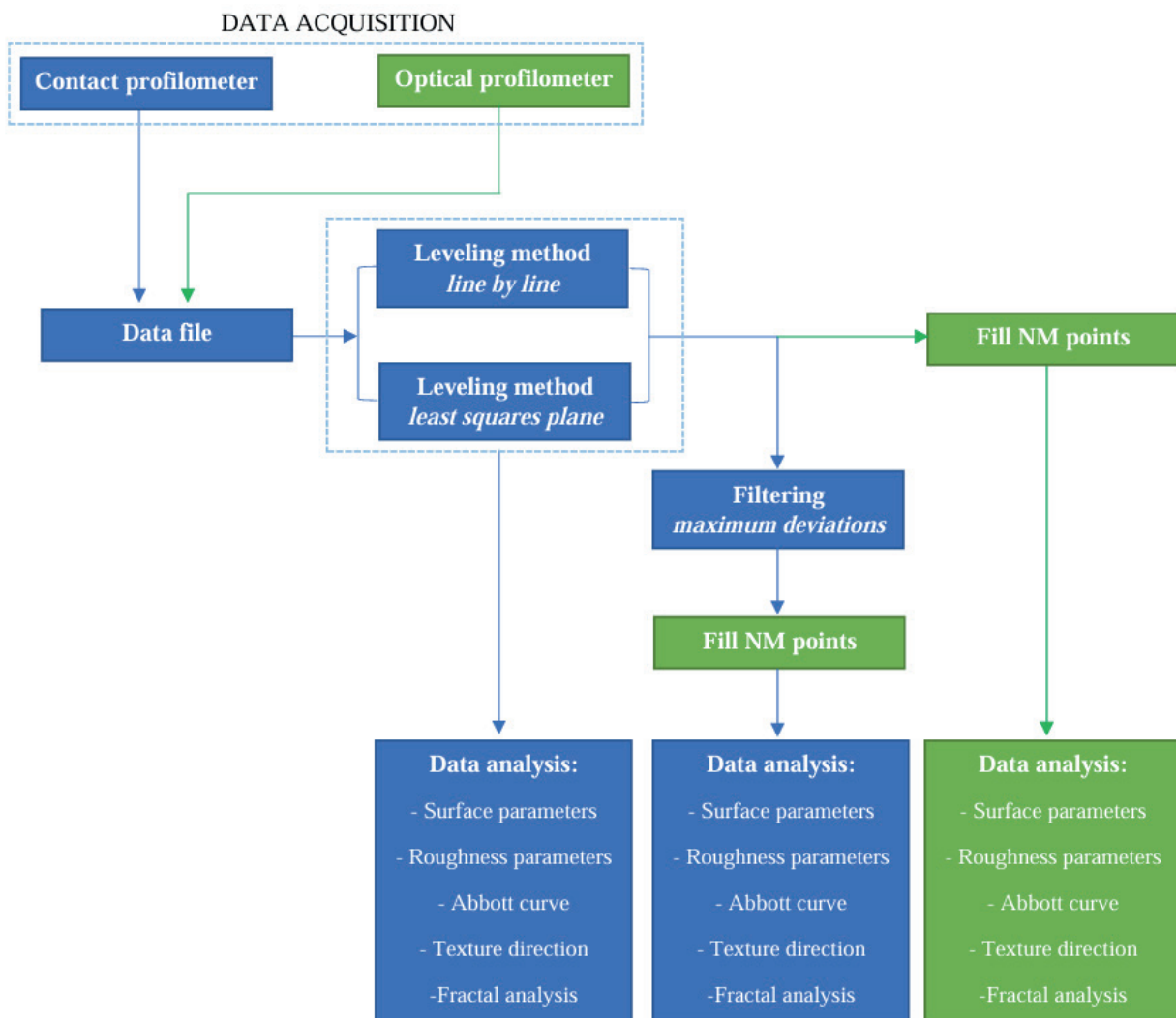


Fig. 2. Measurement data management procedure

The first step was to determine the effect of the chosen type of surface levelling on the data obtained. Two main types of levelling were tested:

- levelling least square plane (LS),
- levelling line by line (LbL).

Levelling should be regarded as the most important step in data preparation. This is because the amplitude parameters (as well as the removal of the shape of the cylindrical surface under test when using line by line method) depends on the type of selected levelling method.

The next procedure for the data prepared in this way was to remove outliers (RO). This operation is crucial as it reduces interference and minimizes the number of possible errors arising during data acquisition. Examples include point and local contamination on the surveyed surface, vibrations or other non-periodic disturbances. Often, maximum deviations are characterised by a spike in the amplitude value of the surface, which should not be taken into account during the analysis. Removal of maximum deviations is particularly recommended for optical measurements.

Due to the use of optical measurement techniques, the effect of filling in non-measured points (NM) was independently investigated. This represented the third operation on the data. The removal of maximum deviations was carried out together with the filling in non-measured points (NM). This operation is marked in

green in the diagram (fig. 2) and is only used for optical measurements. In case of contact measurements, it is not necessary to apply this operation, so this step is omitted. The data recorded according to the procedure shown were collated and compared, determining the effect of each operation on the results obtained.

### 3. Results and Discussion

For the presentation of the results of the developed procedure, a surface made of M1E copper shaped by blasting with an abrasive operating pressure of 4 bar and an average abrasive size of 2.75 mm was selected. This type of texture was selected because of its highly isotropic nature and the lack of clear directionality of the structure. This directly affects the parametric representation in particular for the 2D roughness and basic profile parameters. The relationships associated with the input preparation procedure for each material type and geometric surface structure are analogous.

#### 3.1. Stylus profilometry

The surface measured with a Hommel T8000 contact profilometer was entered in the form of a .sur file into a calculation sheet created in the MountainsMap environment, and then analysed according to the procedure described before. The individual views of the surface subjected to the operation are shown in the illustration (fig. 3).

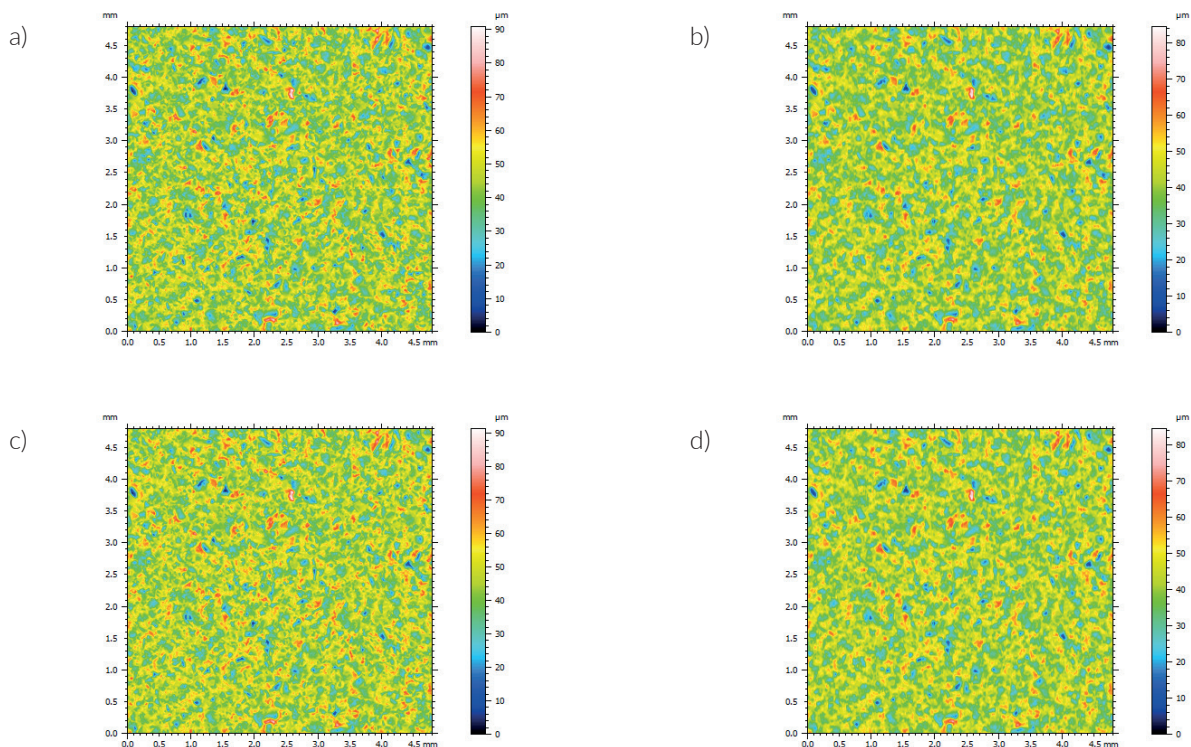


Fig. 3. Surface view for different data preparation procedures - contact profilometer: a) levelling least square plane (LS); b) levelling least square plane (LS) + remove outliers (RO); c) levelling line by line (LbL); d) levelling line by line (LbL) + remove outliers (RO)

The illustration (fig. 3) shows surfaces subjected to different levelling and filtration operations. The greatest differences can be seen between the levelled surface and the surface with the outliers removed. These differences are mainly reflected in the elevation values. It is worth noting that the individual areas are characterised by slightly smoother contours of the visible texture motif. The results of individual operations carried out on the data are also presented in the form of graphs compiling

selected parameters describing the geometric structure of the surface. The data are summarised in the form of spatial parameters (fig. 4) and a 2D group representing basic profile parameters (fig. 5) and roughness (fig. 6).

The graph (fig. 4) shows a summary of the values of selected spatial surface parameters depending on the data preparation operation used.

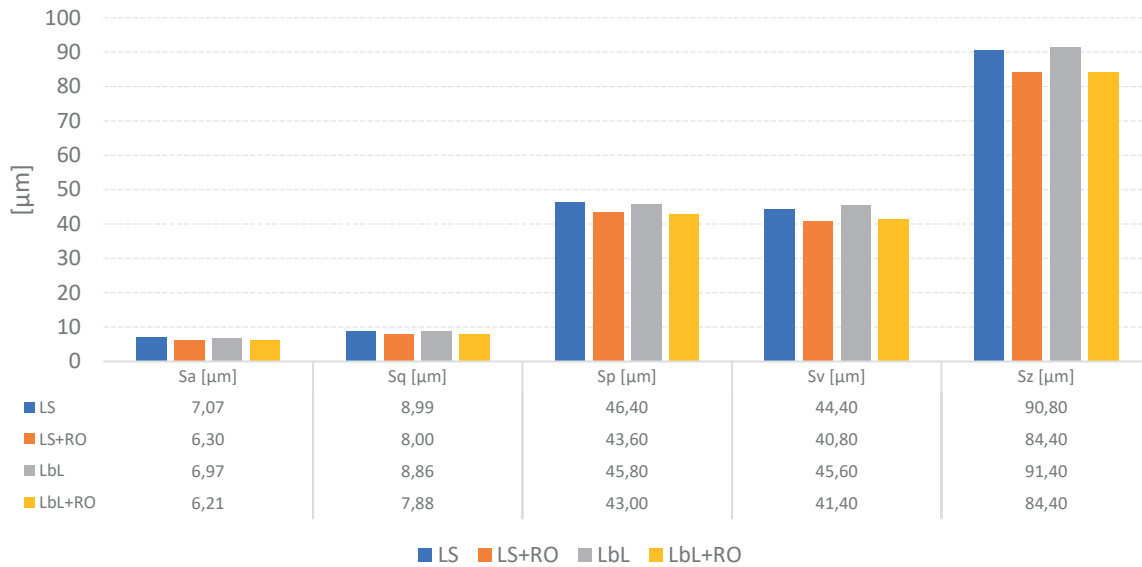


Fig. 4. 3D spatial parameters - contact measurement

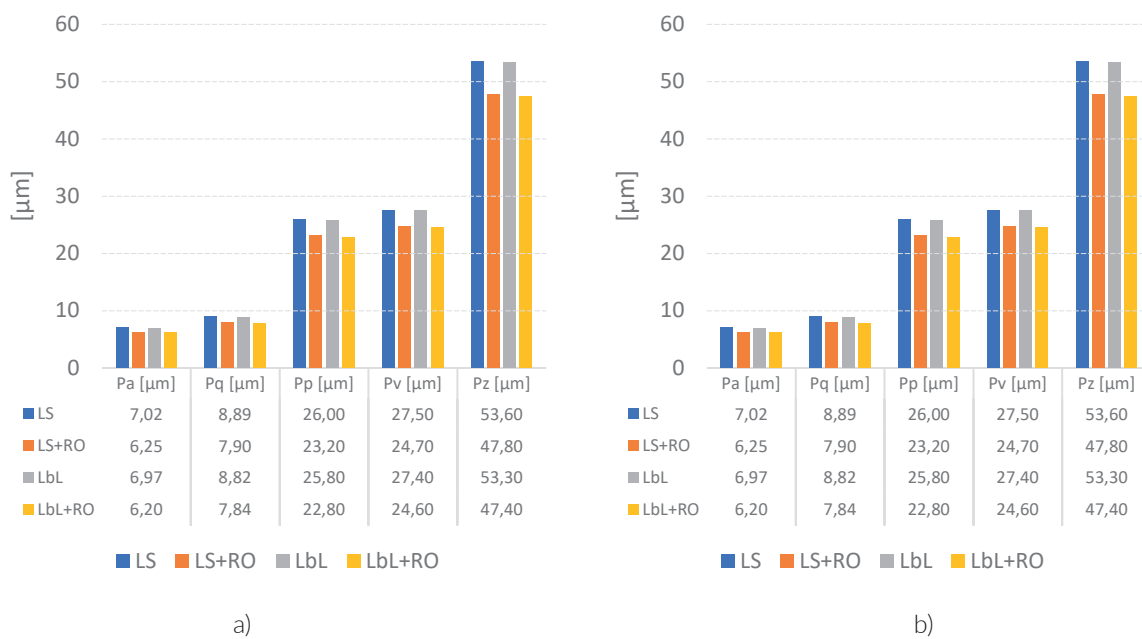


Fig. 5. 2D amplitude parameters for different data preparation procedures - contact measurement: a) basic profile; b) roughness

When analysing the graphs (fig. 4-5), it can be seen that the removal of outliers have a major impact on the relative change in all parameter groups. The largest relative differences were observed for the roughness parameters, amounting to 13 %. For the other groups (spatial parameters and parameters describing the basic profile), the relative differences do not exceed 11.6 %. It should be noted that the relative difference between the type of levelling used (LS/LbL) for flat surfaces (devoid of shape error) does not exceed 1 % for data without outliers removed and 6 % with RO.

### 3.2. Optical profilometry

As in the case of the measurement using contact profilometry, the same surface was measured with a Sensofar S neox optical profilometer using the VSI technique. The data obtained were entered into an analogous calculation sheet to maintain the methodology, the sequence of procedures used and the filtration parameters adopted. The calculation sheet for the contact profilometer was extended by the procedure of filling in non-measured points for each levelling variant. The illustration (fig. 7) shows plots (for the case of the least square plane levelling) showing the influence of the individual steps on its graphical representation.

The data presented (fig. 6) show the areas subjected to selected levelling and filtering operations, as well as filling in non-measured points, which is particularly important for optical measurements. Filling in non-measured points was carried out independently for the levelling variant (fig. 6b) and for the procedure including removal of outliers. It is worth noting that filling in non-measured points is a prerequisite in many cases of surface analysis, particularly for fractal analysis. The degree of occurrence of non-measured points can also vary with the type of measurement technique used or the surface structure itself, its reflectivity or material.

The results of each operation carried out on the data (including all levelling methods used) are also presented in the form of parametric charts. The data is summarised in two groups: the levelling least square plane with individual analysis sequences is presented in the charts (fig. 7 and 8), and the levelling method line by line (fig. 9-10). The data present the values of the 3D and 2D spatial parameters for the basic profile and roughness.

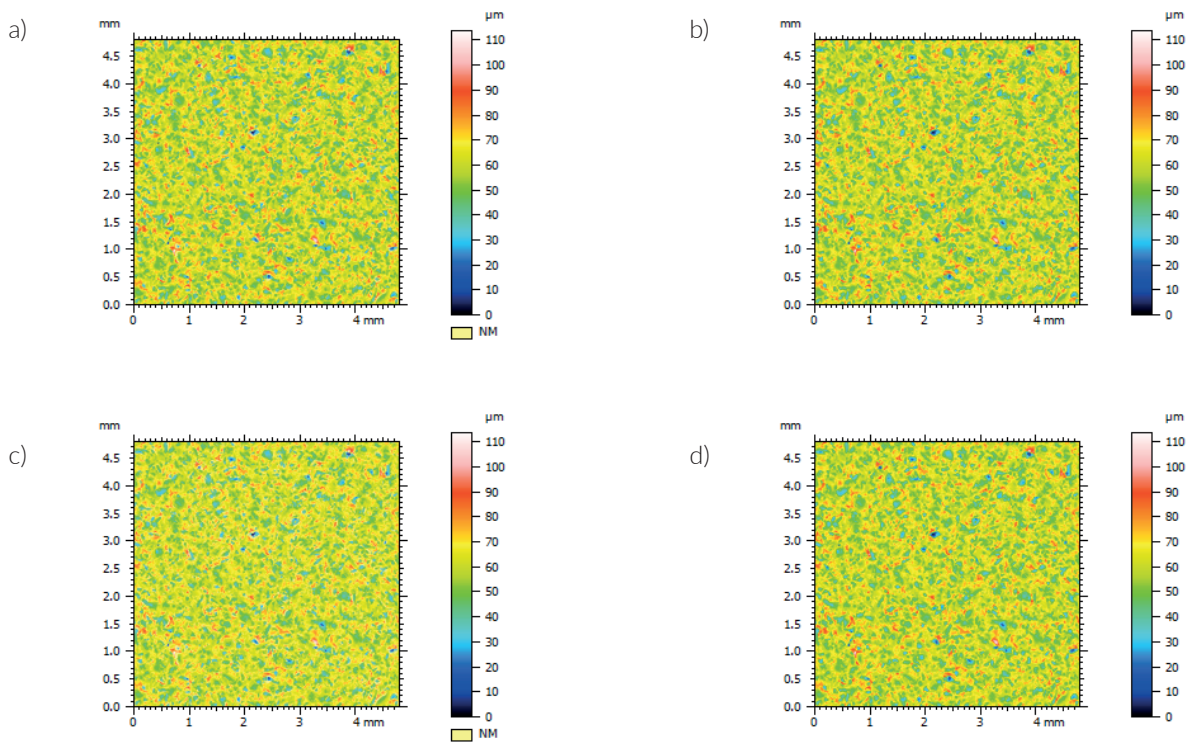


Fig. 6. Surface view for effects of different data preparation procedures - optical profilometer: a) levelling least square plane (LS); b) LS + fill in non-measured points (NM); c) levelling least square plane (LS) + remove outliers (RO); d) LS + RO + fill in non-measured points (NM)

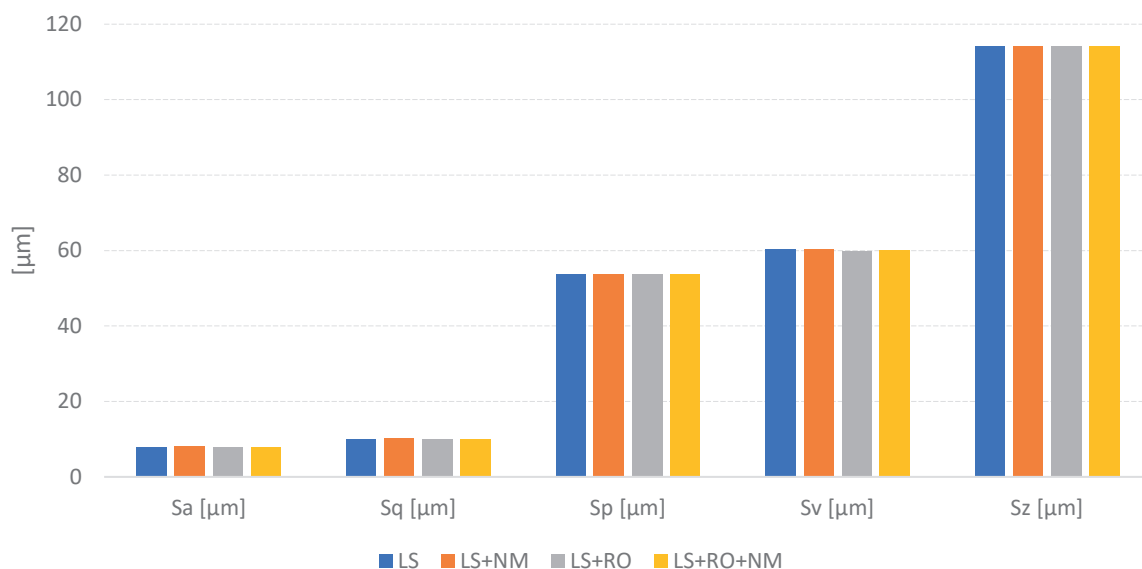


Fig. 7. 3D spatial parameters - optical levelling method (LS)

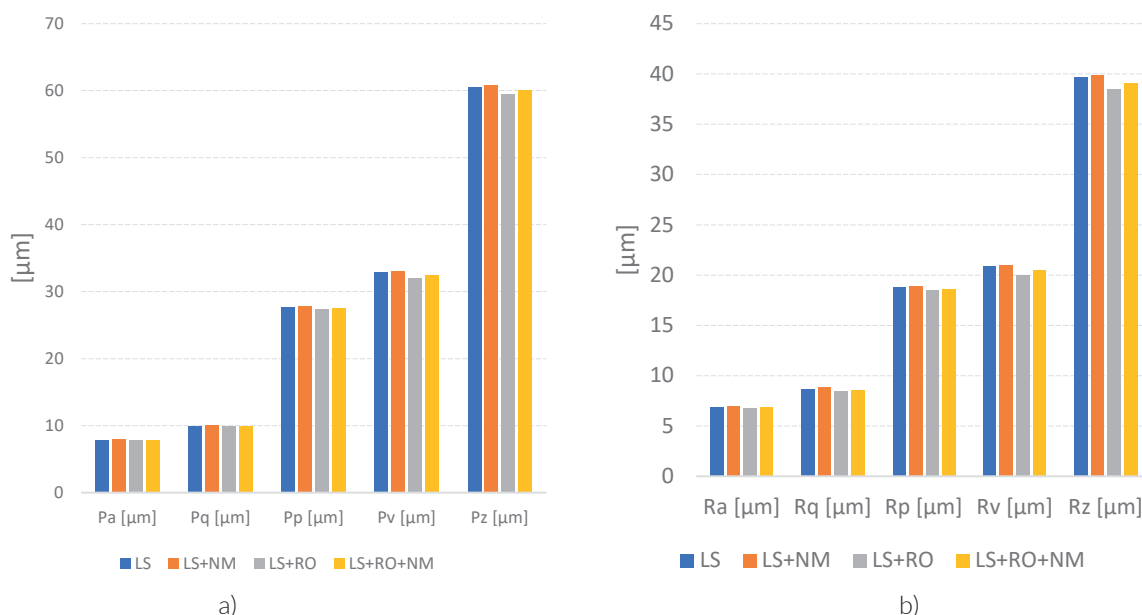


Fig. 8. 2D amplitude parameters for different data preparation procedures (LS) - optical measurement: a) basic profile; b) roughness

An analogous comparison of results was used in case of the non-contact technique. In this comparison, the effects on the parameters of geometric structure of the surface (GSS) and of filling in non-measured points, were also taken into account. Analysing the chart of spatial parameters (fig. 7), no significant differences in parameter values are observed regardless of removing outliers and/or filling in non-measured points (NM). The maximum relative difference is 1.1 %. For the parameters describing the base profile and roughness parameters (fig. 8b), for a presented data preparation procedure, the values obtained with outliers removed are smaller. The highest relative difference for the surface roughness parameters is 4.3 % and for the parameters describing the base profile is 2.7 %.

For optical measurements using the data preparation procedure (LbL), it was observed that removal of outliers had an effect on the relative change in each of the groups of parameters analysed. The analysis showed that the largest relative difference (4.3 %) was observed for the roughness parameters. For the spatial parameters the relative difference is 1.7 % and for the parameters describing the base profile 3.4 %.

In the prepared data using the LS and LbL methods in the optical measurements including filling in non-measured points (NM), differences in the values obtained are noted. The maximum relative difference (LS+NM/LbL+NM) is equal to 2 %. The additional use of remove outliers reduces this difference to 1.7 %.

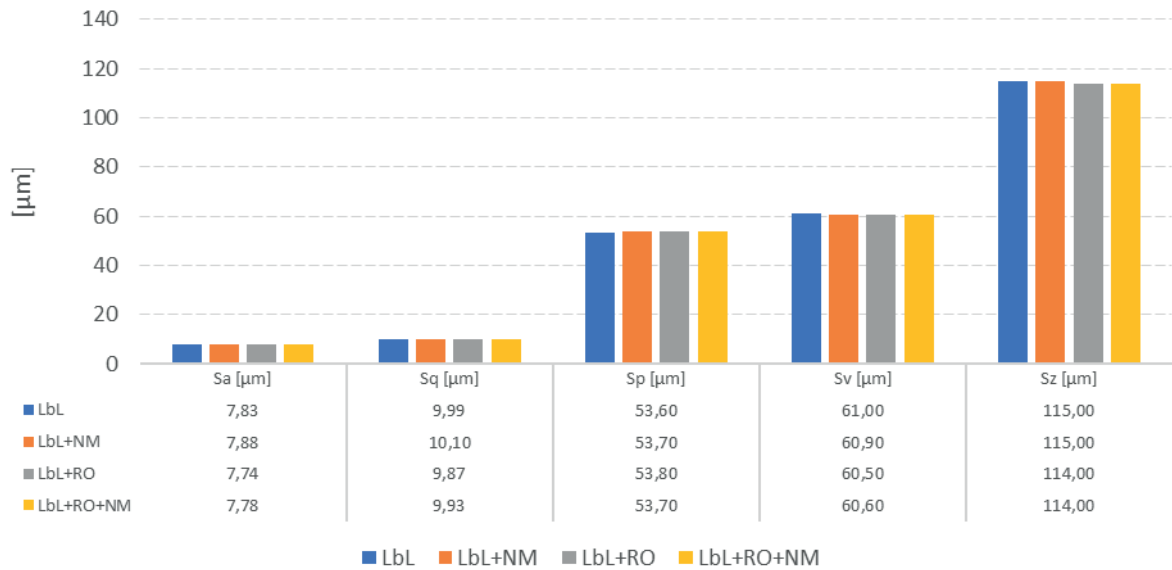


Fig. 9. 3D spatial parameters - optical measurement by levelling method (LbL)

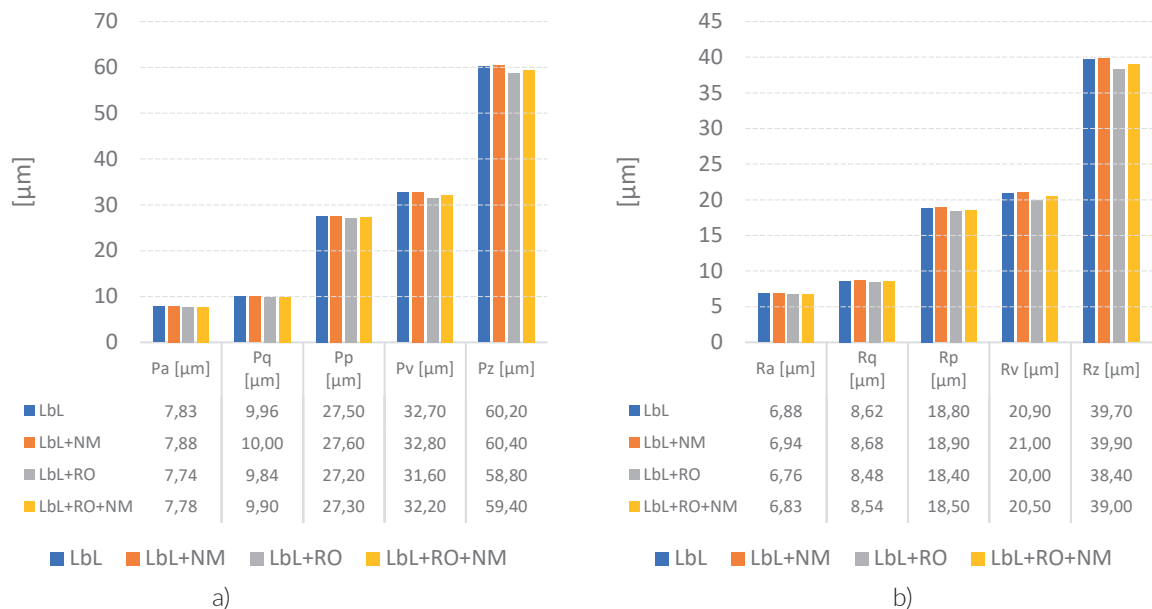


Fig. 10. 2D amplitude parameters for different data preparation procedures (LbL) - optical measurement: a) basic profile; b) roughness

Despite its versatility, the applied methodology carries certain limitations. For periodic surfaces, an individual approach to levelling is necessary, particularly using LbL to determine the specific direction. In the case of optical measurements, it is essential to independently verify the filling of unmeasured points and select an appropriate degree of approximation for the filling. Despite these limitations, the data preparation method is highly effective and proves to be significantly useful in comprehensive surface roughness analyses.

## Conclusions

The article presents selected procedures for preparing input data for contact and optical profilometry that affect the representation of surface irregularities. After analyzing the research results, the following conclusions were formulated:

- During analysis of the data sets for both the contact profilometry and optical profilometry techniques, it was found that the parametric representation describing the surface structure is most influenced by filtering – removal of outliers (RO). The relative differences between the data for which this operation was not

applied are 13 % for contact profilometry and ~1 % for optical profilometry, respectively.

- This is related to the fact that all unitary features are removed from the surface, which deviate from the fundamental part of the irregularities present and may represent environmental disturbances. It should be borne in mind that this operation is useful in optical data acquisition, where the measurement is affected by material/surface reflectivity, light polarisation and wavelength.
- The levelling method is also an important issue affecting the results. Although, for the presented data set, the differences between the methods are small and do not exceed <5 %, in some cases they can significantly influence the values of the obtained results.
- This is particularly relevant for cylindrical surfaces or those with irregularities, particularly waviness. If the levelling least square plane method is used, the surface irregularities will be taken into account in the parametric analysis as a whole. In the case of the line by line method, it is possible to remove a shape (e.g. a cylinder) when levelling in a direction parallel to the height of a cylinder.
- The parameter values obtained from the measurement on the presented data set are least influenced by the filling in non-measured points (NM) procedure.
- This operation is mainly used for optical measurement techniques. It conditions the coverage of the entire area with data (approximation of data on the basis of values adjacent to NM).
- On the other hand, this operation can be of great importance and significantly affect parameter values when the surface is reflective or anisotropic and the degree of coverage of the surface with measurement points will be limited. This was confirmed by an independent study on a different data set, which in turn will be the subject of a separate publication.
- It is worth noting that as the number of NM points increases, the value of the standard deviation increases.
- The use of filling in non-measured points operations in the data preparation process is essential for fractal analysis.

Understanding these relationships will help reduce errors related to measurement procedures and data preparation for research, as well as allowing a proper assessment of the geometric structure of the surface.

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## References

- [1] Maruda R.W., Królczyk G.M., Wojciechowski S., Powalka B., Kłos S., Szczotkarz N., Matuszak M., Khanna N., Evaluation of turning with different cooling-lubricating techniques in terms of surface integrity and tribologic properties. *Tribology International*, (2020), vol. 148, s. 106334-1-106334-14.
- [2] Leach R.K., *Characterisation of areal surface texture*. Springer-Verlag; 2013. <https://doi.org/10.1007/978-3-642-36458-7>.
- [3] Thomas T.R., Roughness and function. *Surf Topography: Metrol Prop* 2013;2: 014001. <https://doi.org/10.1088/2051-672X/2/1/014001.1>.
- [4] Mathia T.G., Pawlus P., Wieczorowski M., Recent trends in surface metrology. *Wear* 2011;271(3-4):494-508. <https://doi.org/10.1016/J.WEAR.2010.06.001>.
- [5] Leach R.K. *Optical measurement of surface topography*. Springer; 2011. <https://doi.org/10.1007/978-3-642-12012-1>.
- [6] Ghodrati S., Kandi S.G., Mohseni M., Nondestructive, fast, and cost-effective image processing method for roughness measurement of randomly rough metallic surfaces. *J Opt Soc Am A* 2018;35(6):998-1013. <https://doi.org/10.1364/JOSAA.35.000998>.
- [7] Kiran M.B., Ramamoorthy B., Radhakrishnan V., Evaluation of surface roughness by vision system *Int J Mach Tool Manufact* 1998;38(5-6):685-90. [https://doi.org/10.1016/S0890-6955\(97\)00118-1](https://doi.org/10.1016/S0890-6955(97)00118-1).
- [8] Su R., Wang Y., Coupland J., Leach R.K., On tilt and curvature dependent errors and the calibration of coherence scanning interferometry. *Opt Express* 2017;25(4): 3297-310. <https://doi.org/10.1364/OE.25.003297>.
- [9] Su R., Kirillin M., Ekberg P., Roos A., Sergeeva E., Mattsson L., Optical coherence tomography for quality assessment of embedded microchannels in alumina ceramic. *Opt Express* 2012;20(4):4603-18. <https://doi.org/10.1364/oe.20.004603>.
- [10] 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* Volume 121, June 2018, Pages 225-239.
- [11] 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.
- [12] 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.
- [13] 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.
- [14] Józwiak J., Mika D., Diagnostics of workpiece surface condition based on cutting tool vibrations during machining. *Adv. Sci. Technol. Res. J.*, 9 (2015), pp. 57-65, 10.12913/22998624/2365.
- [15] Mikołajczyk T., Nowicki K., Bustillo A., Pimenov D.Y., Predicting tool life in turning operations using neural networks and image processing. *Mech. Syst. Signal Process.*, 104 (2018), pp. 503-513, 10.1016/j.ymsp.2017.11.022.
- [16] Wojciechowski S., Krajewska-Śpiewak J., Maruda R.W., Krolczyk G.M., Nieslony P., Wieczorowski M., Gawlik J., Study on ploughing phenomena in tool flank face - workpiece interface including tool wear effect during ball-end milling. *Tribology International*, (2023), vol. 181, s. 108313-1-108313-20.
- [17] Wojciechowski S., Krolczyk G.M., Wiąckiewicz M., Study on metrological relations between instant tool displacements and surface roughness during precise ball end milling. *Measurement*, 129, (2018), s. 686-694.
- [18] Przestacki, Szymanski P., Wojciechowski S., Formation of surface layer in metal matrix composite A359/20SiCP during laser assisted turning. *Composites Part A: Applied Science and Manufacturing*, 91, 1, (2016).
- [19] Lu E., Ren W., Dai H., Zhu X., Investigations on electromagnetic wave scattering simulation from rough surface: Some instructions for surface roughness measurement based on machine vision. *Precision Engineering* Volume 82, July 2023, Pages 156-168.
- [20] Li S., Peng G., Xu D., Shao M., Wang X., Yang Q., A multifeature fusion model for surface roughness measurement of cold-rolled strip steel based on laser speckle. *Measurement*, Volume 227, 15 March 2024, 114319.
- [21] Al-Kindia G.A., Shirinzadeh B., An evaluation of surface roughness parameters measurement using vision-based data. *International Journal of Machine Tools & Manufacture* 47 (2007) 697-708.

- [22] Zhang H., Liu J., Chen S., Wang W., Novel roughness measurement for grinding surfaces using simulated data by transfer kernel learning. *Applied Soft Computing* Volume 73, December 2018, Pages 508-519.
- [23] Weckenmann A., Krämer P., Assessment of measurement uncertainty caused in the preparation of measurements using computed tomography. XIX IMEKO World Congress, Fundamental and Applied Metrology, September 6–11, 2009, Lisbon, Portugal.
- [24] Whitehouse D., *Surfaces and Their Measurement* Elsevier Ltd.; 2004. 432 p.
- [25] Yuan Y.B., Qiang X.F., Song J.F., Vorburger T.V., A fast algorithm for determining the Gaussian filtered mean line in surface metrology. *Precision Engineering* 2000; 24:62–9.
- [26] Yuan Y.B., Vorburger T.V., Song J.F., Renegar T.B., A simplified realization for the Gaussian filter in surface metrology, X International Colloquium on Surfaces 2000, Chemnitz, Germany, 2000. pp. 133–141.
- [27] Numada M., Nomura T., Yanagi K., Kamiya K., Tashiro H., High-order spline filter and ideal low-pass filter at the limit of its order. *Precision Engineering* 2007; 31:234–42.
- [28] Hanada H., Saito T., Hasegawa M., Yanagi K., Sophisticated filtration technique for 3D surface topography data of rectangular area. In: *Proceeding's 10th International Conference "Metrology and Properties of Engineering Surfaces"*. 2005. p. 191–8.
- [29] Jiang X., Zeng W., Scott P., Ma J., Blunt L., Linear feature extraction based on complex ridgelet transform. In: *Proceedings of the 10th International Conference on Metrology and Properties of Engineering Surfaces*. 2005. p. 85–92.
- [30] Jiang X., Scott P.J., Whitehouse D.J., Blunt L., Paradigm shift in surface metrology. Part II. The current shift. *Proceedings of the Royal Society A* 2007;463: 2071–99.
- [31] Barrios-Muriel J., Salgado D.R., Cambero I., Alonso F.J., González A.G., An approach for Surface Roughness Filtering as an alternative to ISO Standard. *Procedia Manufacturing* 41 (2019) 674–681.
- [32] Zakharov O.V., Lysenko V.G., Ivanova T.N, Asymmetric morphological filter for roughness evaluation of multifunctional surfaces. *ISA Transactions*, <https://doi.org/10.1016/j.isatra.2023.12.016>.