Assessment of Surface Structure of Machined Surfaces

David Dobrocký, Zbyněk Studený, Zdeněk Pokorný, Zdeněk Joska, Petr Faltejsek
Department of Mechanical Engineering, Faculty of Military Technology, University of Defence in Brno, Kounicova 65, 602 00 Brno, Czech Republic. E-mail: david.dobrocky@unob.cz, zbynek.studeny@unob.cz, zdenek.pokorny@unob.cz, zdenek.joska@unob.cz, petr faltejsek@unob.cz

This paper deals with basic methodology of surface evaluation of functional surfaces, which were prepared by various machining methods (turning, milling and grinding). Here are the basic 2D (profile) parameters and 3D (spatial) parameters and their properties in relation to the machined surface. Parameters of machined surfaces were obtained by CCI Lite Coherence Correlation Interferometer from Taylor Hobson and evaluated using the TalyMap Platinum software. The article further demonstrates the inappropriateness of the surface structure assessment with only the parameter Ra (mean arithmetic deviation of the profile), which is the most common method in technical practice. This methodology extends the possibilities of a comprehensive assessment of exposed surfaces of machine parts.

Keywords: Surface, structure, microgeometry, profile parameters, machining

1 Introduction

At present, demands for the functional properties of machine parts are increasing. One of the important qualitative requirements for functional properties of components is the surface quality of the exposed surfaces [1, 2, 3]. Any technological method used in the realization of the surface of the technical surfaces leaves the inequalities that are essential in the function of these surfaces [4, 5, 6, 7]. Inequalities represent a spatial structure whose complex assessment is quite problematic. The problem of assessing unevenness of the surface (its structure) is primarily solved in the technical practice by reducing it to the plane of the cut with a plane perpendicular to the surface. A profile (2D profile) is obtained at the plane of the cut, which is the basic source of information for surface structure assessment. A more comprehensive solution is to assess the surface structure using 3D assessment. The 3D assessment provides practical information on the relationships between the geometric characteristics of the surface and its functional properties [8, 9]. The disadvantage of 3D evaluations is higher demands on measuring technology and evaluation software [10].

Today's surface roughness assessment is prescribed by EN ISO 4287, 3D surface texture assessment is given in EN ISO 25178 [11]. Although the possibilities of describing surface microgeometry over the past are considerably wider [12, 13], there is still no more detailed assessment of machined surfaces in technical practice. There are indeed a number of reasons that have supported and still support the simplicity and brevity of the prescription system and roughness assessment. It is still required that the surface roughness assessment be relatively inexpensive, both with regard to the cost of the necessary measuring instruments and the ease and speed of measurement. The values obtained show relatively good reproducibility. Simple marking of surface roughness in drawings or in other production documentation is also required. Let us also recall that many technicians are still convinced that for prescribing of the surface microgeometry only the value of the Ra characteristic is sufficient [14, 15]. This view stems from underestimation and ignorance of the issue.

For a more detailed assessment of the functional surface, a much more accurate and mainly, more complete analysis of the surface microgeometry is needed. Thus, it is clear that the basic prerequisite for any surface classification is as precise and complete as possible description of its microgeometry.

The paper deals with evaluation of machined surfaces of samples made of CSN 41 2050 steel. The samples were made by different machining technologies for comparison of periodic (turning and milling) and non-periodic surfaces (grinding), both in terms of microgeometry, and as well as achieved 2D and parameters of surface roughness and 3D parameters of surface texture. The aim of the paper is to confirm the importance of describing the surface roughness with more 2D roughness parameters than with just one parameter Ra, which is most commonly used in engineering practice. Using more parameters gives us a more detailed picture of the real profile of the machined surface and its behaviour during load. Furthermore, the importance of surface texture evaluation using 3D surface parameters is shown. Based on these parameters, we are able to evaluate the relationship between the geometric characteristics of a surface and its functional properties. 3D surface parameters provide information about the surface's ability to retain the lubricant or to predict the durability of a functional surface in terms of wear.

The chosen machining technologies have been chosen taking into account the fact that even using diametrically different machining technologies and parameters can measure almost the same surface roughness. Different tool geometry and machining principle can lead to a surface with a similar value of Ra parameter. However, only the use of more detailed analysis of 2D surface profile, which is described by more parameters, allows to distinguish significant differences in surface microgeometry. Different surface microgeometry causes different load behaviour of these surfaces. These differences are further confirmed in the evaluation of 3D surface parameters,

where the surface morphology typical for individual machining technologies stands out.

2 Results and discussion

In order to evaluate the microgeometry of the surface and its more complete quantification, the basic amplitude (height) characteristics of the surface profile (2D parameters) were chosen:

- Ra – Arithmetic Mean Deviation of the roughness profile. It only shows the mean value of the coordinates of each point of the surface profile curve. On rugged surfaces, broken by pores, etc., it fails and leads to mistakes. The measure of validity of the Ra characteristic is the asymmetry Sc. The Ra characteristic does not give an idea of the shape of the surface profile (Fig. 1). Yet it is widely used and defended. Surfaces with the same Ra value may behave differently in functional loads. Different surface profile shapes affect the Ra value at the same highest height of the profile Rz.
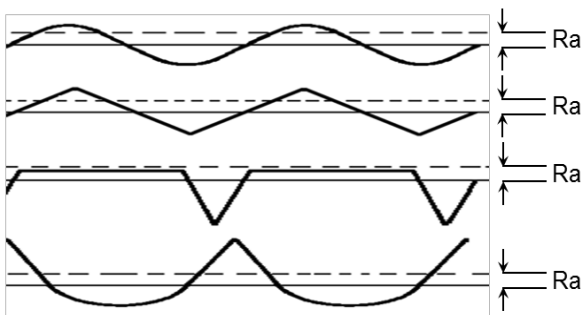

Fig. 1 *Various surface profile shapes at the same value of Ra parameter*

- Rq – Root-Mean-Square (RMS) Deviation of the roughness profile. It is more sensitive when expressing deviations from the shape-homogeneous profile. It has a highlighting effect on individual random peaks and valleys. A parameter capable of distinguishing between a very fine surface and a surface similar to atypical traces and defects. For statistical processing, Rq values are more significant than Ra. In some literature, the ratio $Rq = 1,1Ra$ is indicated, indicating the practical equivalence of both characteristics, considering the measurement inaccuracy or the measurement site selection.

- Rz – Maximum Height of the roughness profile. This parameter is similar to Rt, but it is slightly more stable due to averaging over several basic lengths. Rz is an alternative to Rt as a control parameter. It is suitable for evaluation of rough profiles. On contact surfaces (e.g., plain bearings) it expresses the likelihood that the oil film profile will penetrate.

- Rt – Total Height of the roughness profile. Rt determines the maximum distance between the peak and the valley of the profile at the evaluated length (ln). This is a peak parameter that is loaded with large scattering and may be unstable. It shows the extreme boundaries of the profile, but these may not be credible. Rt is used as a control parameter. It is particularly suitable where the surfaces of the parts are exposed to high stress. Individual large peaks can penetrate the oil lubrication film and increase wear, abrasion and damage to sliding surfaces.

From the longitudinal and shape characteristics of the surface profile were selected:

- RSm – Mean Width of the roughness profile elements. It serves for longitudinal (frequency) evaluation of surface roughness, especially periodic profile components. This parameter will help distinguish between smooth and rough surfaces. On smooth surfaces, the value of RSm will be similar to each other. RSm is often numerically equal to the feed of the lathe or grinder and can be used to track the condition of the knife or grinding wheel, or to change the structure of the material.

- Rdq – Root-Mean-Square Slope of the roughness profile. Rdq determines the quadratic mean of the slope of ordinates within the base length range. Higher slope parameters result in higher friction, less reflection of the surface, easier load deformation, greater wear and better adhesion. Smaller slope is characterized by lower vibration and quieter operation.

From the 3D area parameters were selected height parameters:

- Sa – arithmetic mean deviation.
- Sq – root mean square deviation.
- Sz – ten point height.
- St – total height.

Properties of selected 3D height parameters correlate with properties of 2D height parameters (ie. Sa ≈ Ra, Sq ≈ Rq, Sz ≈ Rz and St ≈ Rt). Of course, the 3D height parameters are related to measured area.

Turning, milling and grinding methods were chosen to evaluate the structure of machined surfaces. The CSN 41 2050 steel in the tempered state was used for the evaluation. Three samples were produced from steel for each machining operation. The 2D parameters were analysed

at an assessment length of 4 mm, the sampling length was 0.8 mm. 1024 profiles were obtained from each measurement and the mean value of the profile was taken into account. 3D parameters were analysed on an area of 0.8 mm x 0.8 mm. Measurement was performed using a CCI Lite coherence correlation interferometer. The results were evaluated using the TalyMap Platinum software.

The results of the evaluated 2D and 3D parameters of machined surfaces are documented in Table 1. Table 2 shows the tool types and their parameters and types of used machines. The cutting conditions for the individual machining operations are shown in Table 3.

***Tab. 1** Characteristics of roughness of machined surfaces*

Sample	Roughness parameters									
	Ra (µm)	Rq (µm)	Rz (µm)	Rt (µm)	RSm (mm)	Rdq (°)	Sa (µm)	Sq (µm)	Sz (µm)	St (µm)
Turning										
A1	1.48	1.68	6.25	6.25	0.16	9.91	2.15	2.64	11.51	15.79
A2	2.96	3.35	12.33	12.33	0.24	16.62	3.38	4.05	19.34	20.89
A3	5.32	6.40	24.72	24.72	0.30	22.35	5.79	6.93	35.01	43.82
Milling										
B1	0.96	1.23	6.14	6.14	0.06	14.27	1.01	1.28	8.48	9.26
B2	2.38	2.85	10.44	10.44	0.12	17.10	2.46	2.94	12.61	14.80
B3	5.68	6.64	23.52	23.52	0.19	25.06	5.90	6.81	26.96	32.11
Peripheral grinding										
C1	0.44	0.54	2.66	2.66	0.02	10.20	0.43	0.54	9.50	14.62
C2	0.84	1.07	6.00	6.00	0.04	15.34	0.88	1.14	15.71	22.03
C3	1.58	1.96	9.84	9.84	0.05	19.16	1.73	2.15	13.43	20.11

***Tab. 2** Tools and machines used for machining of experimental samples*

Operation	Turning	Milling	Peripheral grinding
Tool	Holder CTAPR 2020 K 16 (R), carbide insert TPMR 160308E-47, r_e = 0.8 mm, cemented carbide 6630. Machining liquid PARAMO EOPS 1030, 5%.	Face milling cutter CoroMill 210, diameter 42 mm, five teeth, type R210-066C6-14H. Indexable inserts R210-14 05 12M-KM, r_e = 1 mm. Machining liquid PARAMO EOPS 1030, 5%.	Grinding wheel TYROLIT, T1 250x20x76 mm, hardness J, type 98A60J9V40. Machining liquid PARAMO EOPS 1030, 5%.
Machine	Universal lathe SV18RA	Vertical machining center VMS 1000 MAS	Grinding machine BPH20 NA

***Tab. 3** Cutting conditions of machining*

Sample	Operation	Cutting conditions		
		v_c (m.min^{-1})	f (mm)	a_p (mm)
A1	Turning	250	0.1	1
A2			0.2	
A3			0.3	
		v_c (m.min^{-1})	f_z (mm)	a_p (mm)
B1	Milling	180	0.11	0.15
B2		180	0.17	
B3		75	0.31	
		v_c (m.s^{-1})	v_{ft} (m.min^{-1})	f_a (mm)
C1	Peripheral grinding	36	15	4
C2		36	15	6
C3		36	15	8

Fig. 2 shows 2D profiles of surfaces after turning. Profiles after milling are documented in Fig. 3 and Fig. 4 shows the profiles after peripheral grinding.
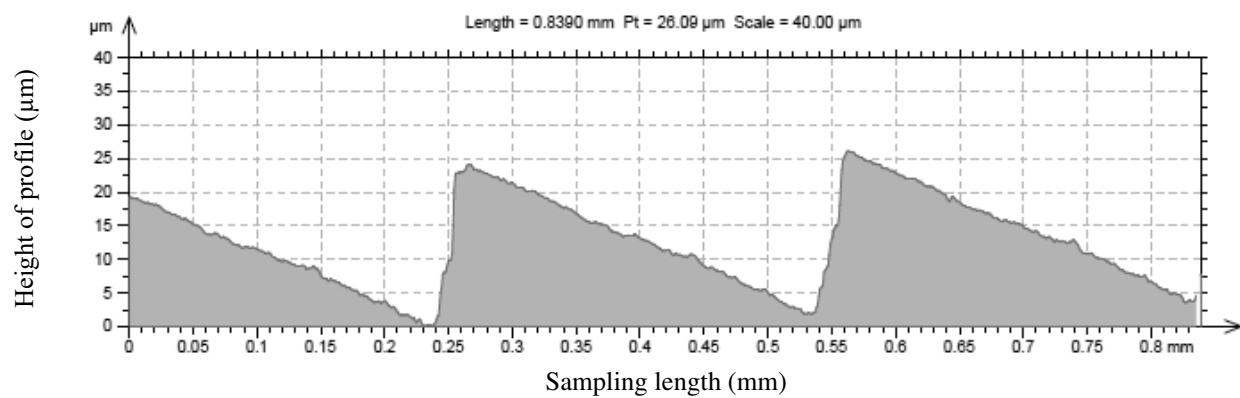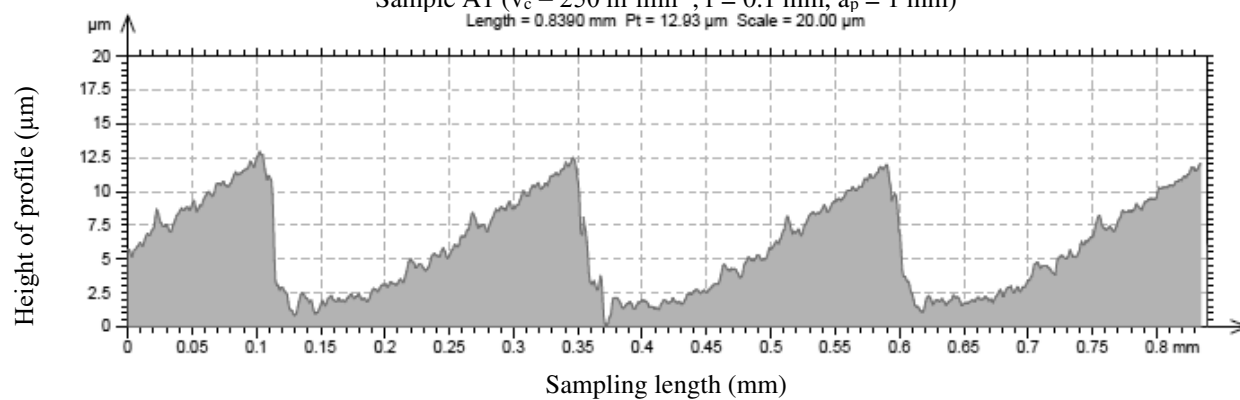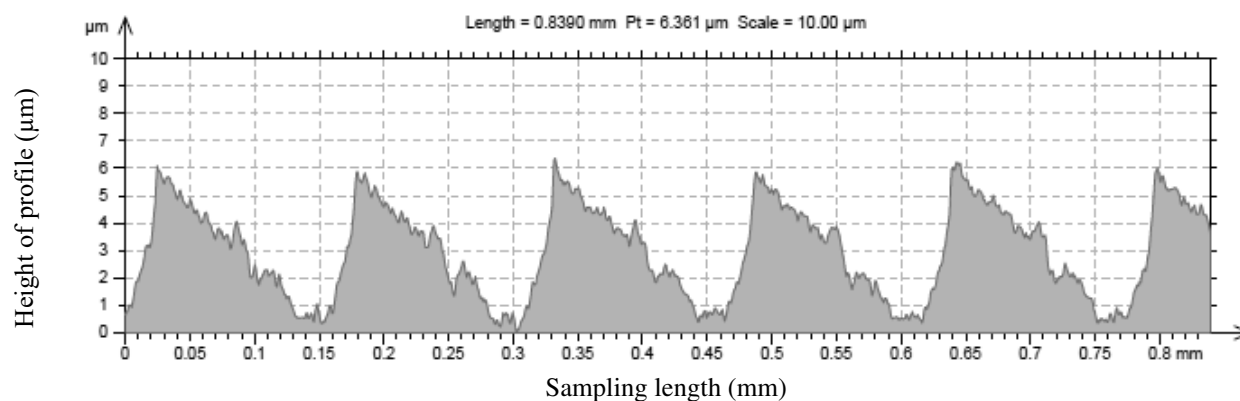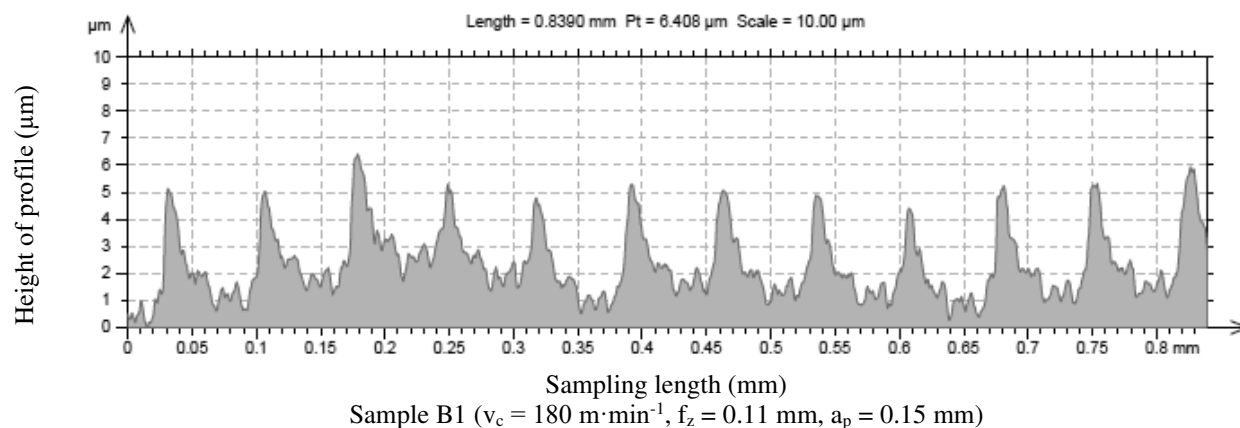
Sample A1 ($v_c = 250$ m·min^{-1}, $f = 0.1$ mm, $a_p = 1$ mm)

Sample A2 ($v_c = 250$ m·min^{-1}, $f = 0.2$ mm, $a_p = 1$ mm)

Sample A3 ($v_c = 250$ m·min^{-1}, $f = 0.3$ mm, $a_p = 1$ mm)

***Fig. 2** Surface profiles after turning*

Sample B1 ($v_c = 180$ m·min^{-1}, $f_z = 0.11$ mm, $a_p = 0.15$ mm)

Sample B2 (v_c = 180 m·min⁻¹, f_z = 0.17 mm, a_p = 0.15 mm)

Sample B3 (v_c = 75 m·min⁻¹, f_z = 0.31 mm, a_p = 0.15 mm)
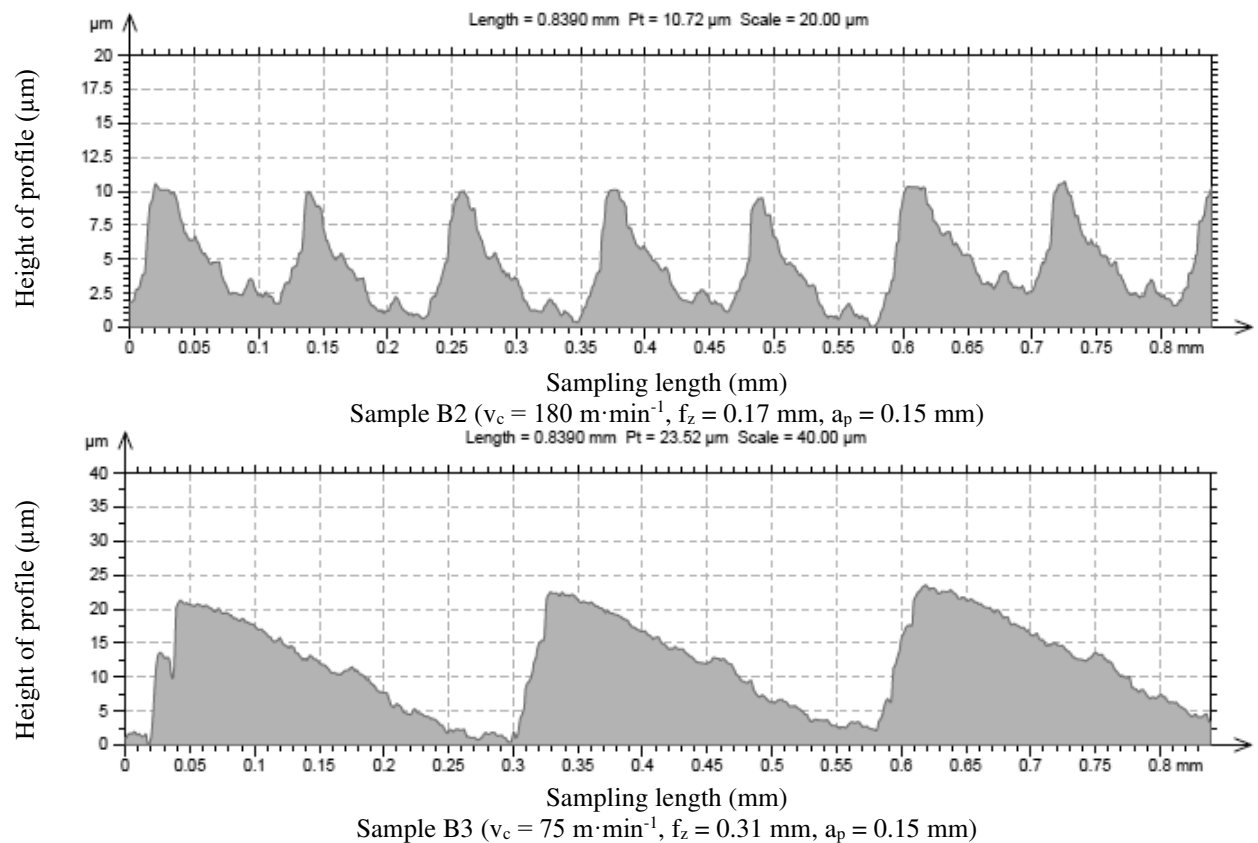
Fig. 3 *Surface profiles after milling*

Sample C1 (v_c = 36 m·s⁻¹, v_w = 15 m·min⁻¹, f_a = 4 mm)

Sample C2 (v_c = 36 m·s⁻¹, v_w = 15 m·min⁻¹, f_a = 6 mm)
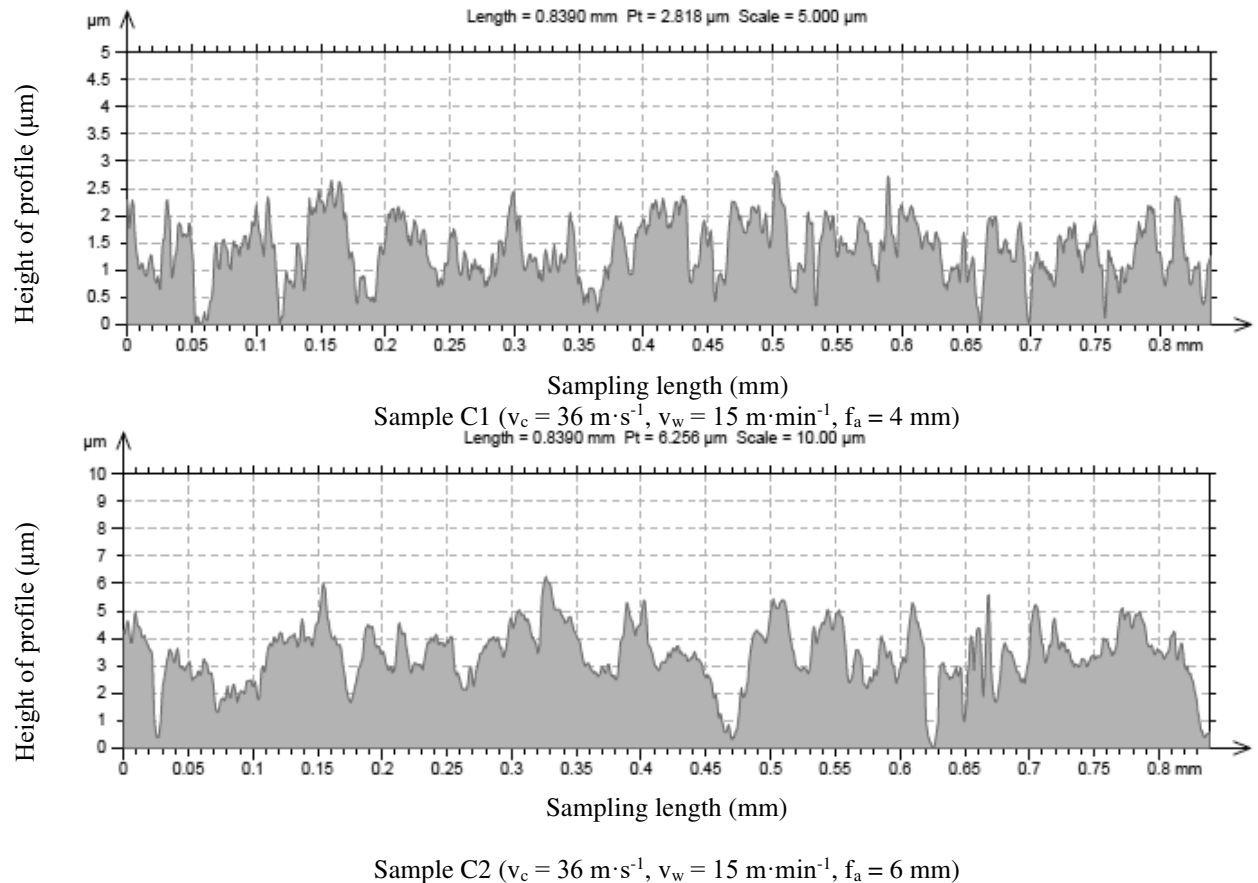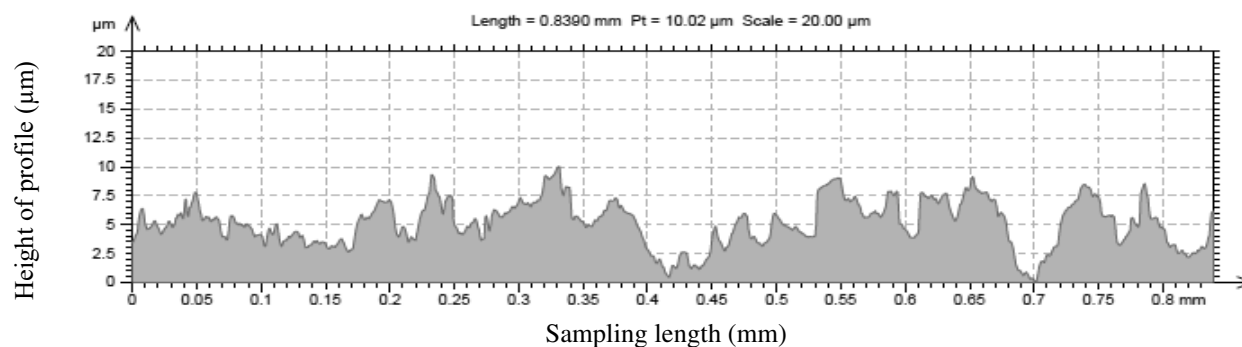
Sample C3 (v_c = 36 m·s⁻¹, v_w = 15 m·min⁻¹, f_a = 8 mm)

Fig. 4 *Surface profiles after peripheral grinding*

Documentation of 3D texture of surfaces according to the chosen machining methods together with the appearance of machined surfaces is shown in Fig. 5 for turned surfaces, Fig. 6 for milled surfaces and Fig. 7 for ground surfaces.
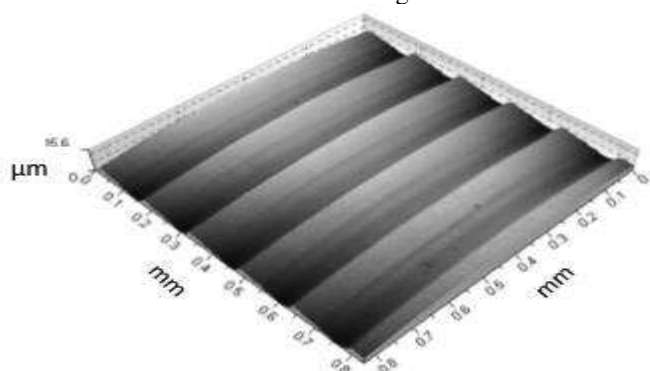
Sample A1 (v_c = 250 m·min⁻¹, f = 0.1 mm, a_p = 1 mm)
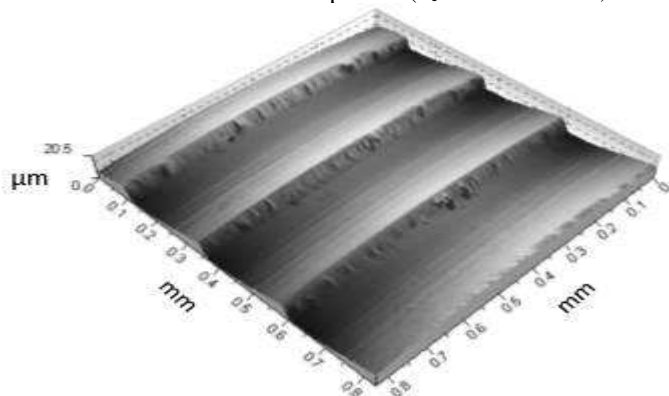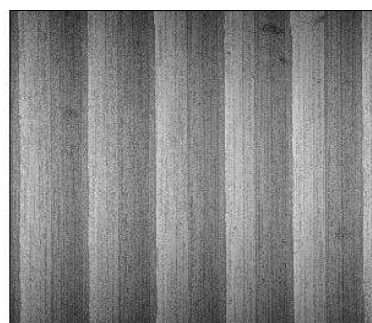
Sample A2 (v_c = 250 m·min⁻¹, f = 0.2 mm, a_p = 1 mm)
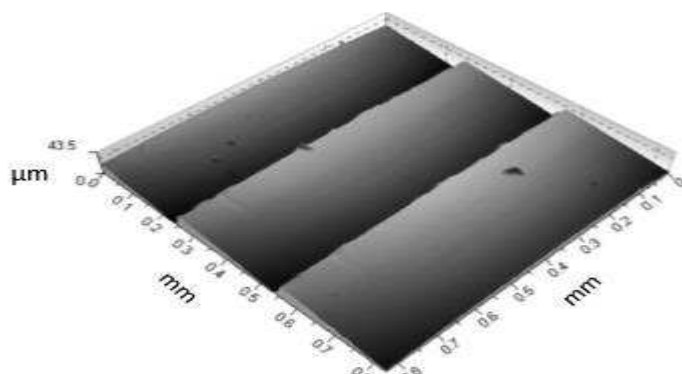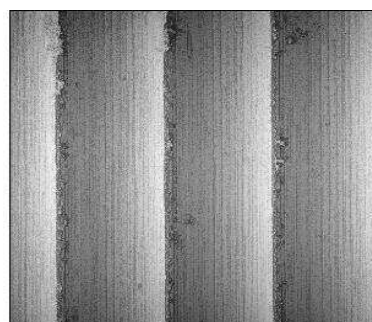
Sample A3 (v_c = 250 m·min⁻¹, f = 0.3 mm, a_p = 1 mm)

Fig. 5 *3D surface texture and appearance of turned surfaces*
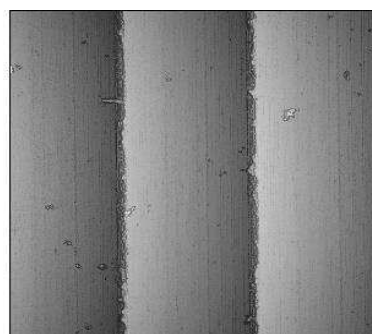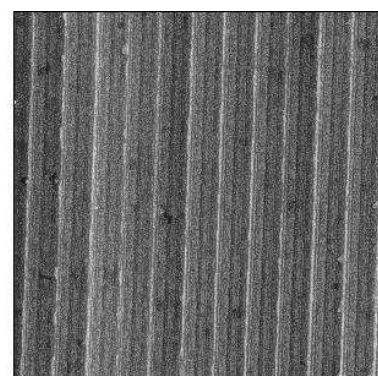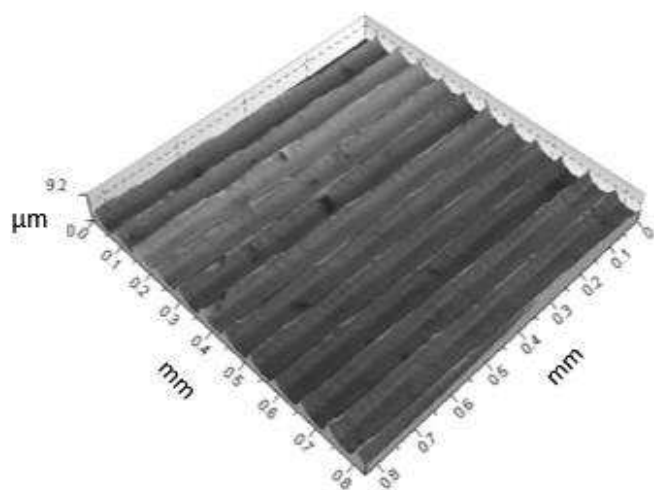
Sample B1 (v_c = 180 m·min⁻¹, f_z = 0.11 mm, a_p = 0.15 mm)
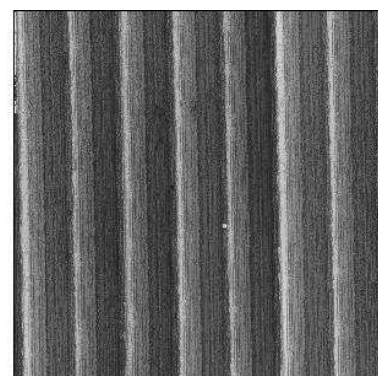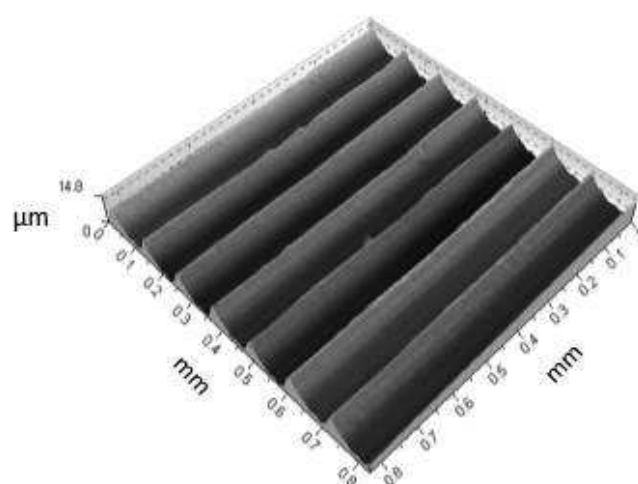
Sample B2 (v_c = 180 m·min⁻¹, f_z = 0.17 mm, a_p = 0.15 mm)
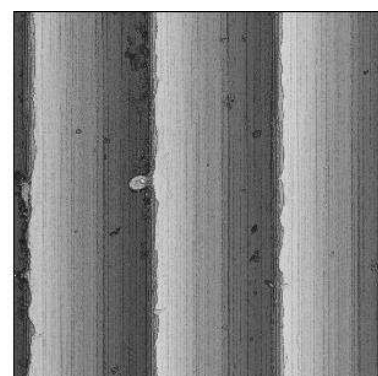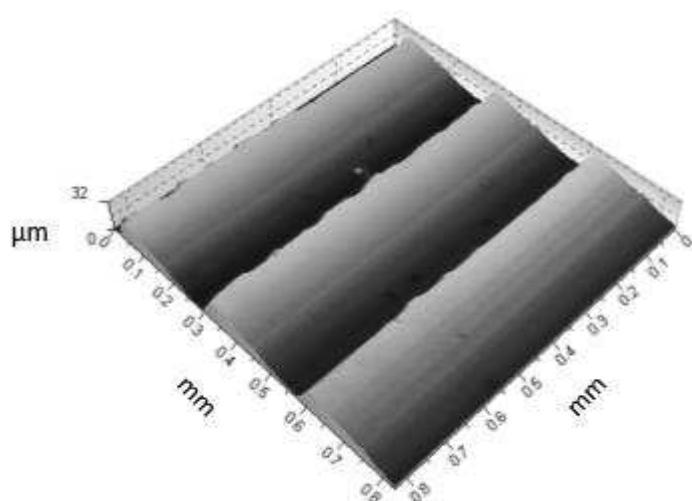
Sample B3 (v_c = 75 m·min⁻¹, f_z = 0.31 mm, a_p = 0.15 mm)

Fig. 6 *3D surface texture and appearance of milled surfaces*
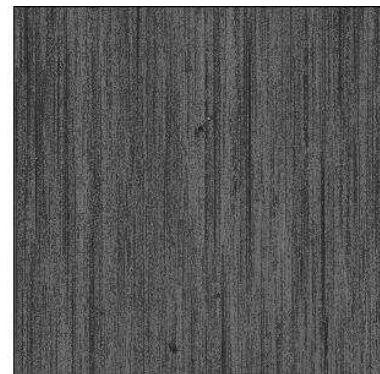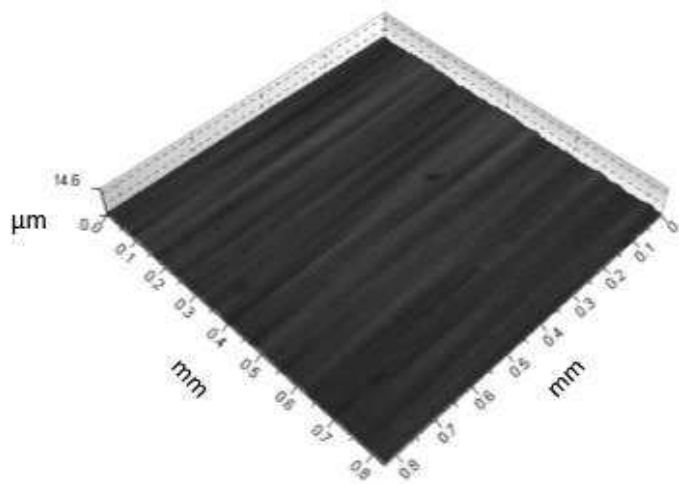
Sample C1 (v_c = 36 m·s^{-1}, v_w = 15 m·min^{-1}, f_a = 4 mm)
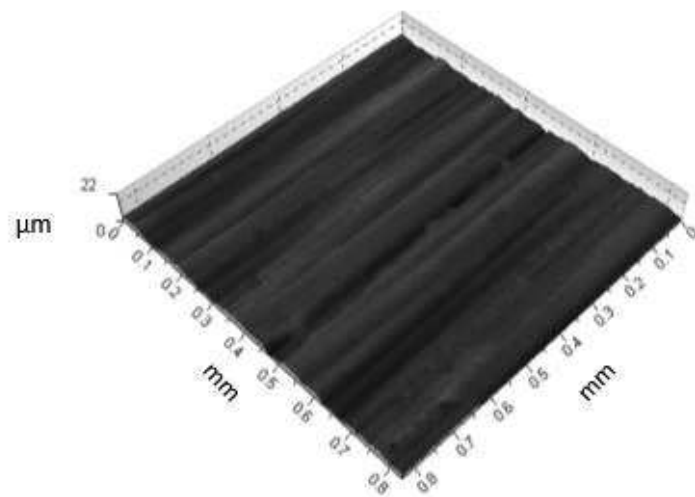
Sample C2 (v_c = 36 m·s^{-1}, v_w = 15 m·min^{-1}, f_a = 6 mm)
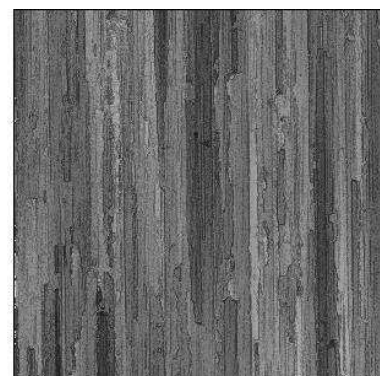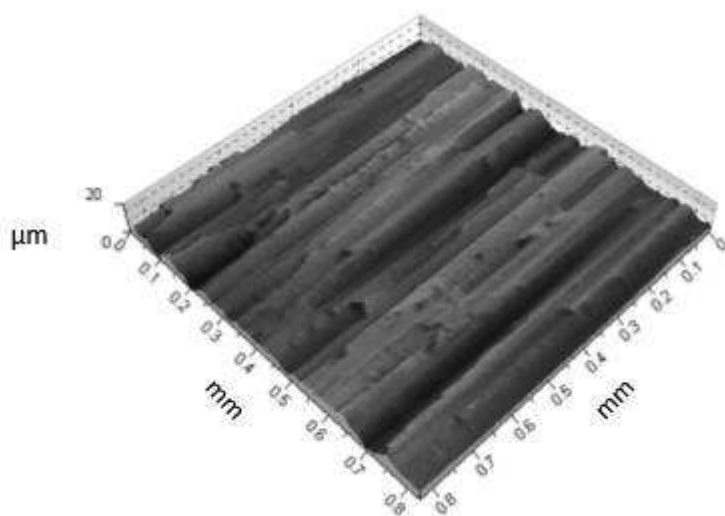
Sample C3 (v_c = 36 m·s^{-1}, v_w = 15 m·min^{-1}, f_a = 8 mm)

Fig. 7 3D surface texture and appearance of ground surfaces

2.1 Evaluation of achieved results

There are no significant differences between the measured characteristics of the individual machining methods, especially for turning and milling operations. The cutting conditions of each operation affect the resulting values of the individual characteristics.

Turning

From the values shown in Table 1, the range of surface roughness achieved can be seen. As the feed value increases, the roughness deteriorates, which corresponds to an increase in the surface texture parameters observed. When increasing the feed value by 100%, there is a 100% increase in the Ra and Rq roughness parameters. Parameters Rz and Rt have reached the same values and determine an increasing profile height, resulting in worse lubrication and running properties of such profiles. The feed value corresponds to the parameter RSm. The slopes of the surfaces, represented by the Rdq parameter, increase again with the feed value, but not linearly.

3D texture surface parameters show similar results to 2D profile parameters. However, with the increase of the feed, the height parameters of the surface Sz and St are increased, which will have a significant effect on the wear of such surfaces.

Fig. 2 documenting profiles of turned surfaces illustrates periodic profiles. The change of feed parameter led to change of the formed surfaces geometry. This shape can also be affected by the wear of the tool and the stiffness of the machine tool [16, 17, 18, 19]. It can be seen from the 3D texture in Figure 5 that when the feed value is increased, the fracture structure is formed on the peaks of the formed surface.

Milling

Milling has resulted in similar results to turning. The periodic profile shows an increase in 2D roughness parameters and 3D surface parameters with rising feed value. The width of the RSm profile elements reaches lower values, but the slope of the surfaces has increased. This is also evident from Fig. 3, where the higher peaks of the formed profile are clearly visible, the profile being different from the turned profile. The similarity with turning is only apparent when the cutting speed and the highest feed value are reduced.

3D parameters correlate with values of 2D amplitude (height) parameters.

Fig. 6 shows finer sawtooth surfaces than in the case of turning. Even in the case of milling under the chosen conditions, surfaces with inappropriate tribological properties have been created.

Peripheral grinding

Grinding as a finishing operation gives the best roughness results. As the depth of cut increased, both 2D and 3D parameters increased, but at higher depths, the increase was slower, which is evident from Table 1. The created profile is non-periodic, see Fig. 4 and Fig. 7, parameter RSm has reached small values. The slope of the Rdq profile has higher values. As the depth of cut increases, the number of peaks and the valleys of the profile

decreases, but at the largest depth of cut there is already a tearing of the surface, as shown in Fig. 7. Such surfaces are then more susceptible to fatigue damage. Tearing of the peaks and filling of the valleys at the greatest depth of cut was also reflected by the reduction of 3D surface texture parameters Sz and St (see Table 1).

Ground surfaces have the best properties in terms of tribological characteristics.

2.2 Unsuitability of the Ra parameter

From the obtained results can be demonstrated the unsuitability of using only the Ra parameter. Comparing the turned surface of sample A1 (Ra = 1.48 μm) and sample surface C3 obtained by grinding (Ra = 1.58 μm), it is evident that the Ra values are almost the same (difference of only 0.1 μm can be statistical error). In Figures 2 and 4, however, completely geometrically different surface profiles are recorded. The same result is obtained when comparing 3D texture and surface appearance in Figures 5 and 7 (surface periodic and non-periodic). A similar conclusion can be made by comparing the milled sample B1 (Ra = 0.96 μm) and the ground sample C2 (Ra = 0.84 μm). Already introducing several other basic surface roughness characteristics can help to better describe the surfaces and make them easier to distinguish (see Table 1).

3   Conclusion

The quality of the machined surface, given by the set of roughness characteristics (microgeometry), affects the basic exploitation characteristics of the machine components. The research of the influence of the quality of significant surfaces on the function of the component is and will be given increasing attention. There are a number of standardized characteristics to describe surface quality (microgeometry) and procedures for more comprehensive surface assessment in engineering practice are optimized. Still, it is still customary to characterize roughness with only one parameter, namely Ra. The article presented the basic characteristics of surface roughness (2D and 3D parameters), which extend the possibilities of description and identification of surfaces produced by different machining technologies. If these parameters are included in the assessment methodology for machined surfaces, we are able to significantly optimize functional surface assessments.

It has been shown in the work that in case of evaluation of surface roughness only by the Ra parameter, real texture of created surface can be characterized wrongly. Two completely different surfaces created by different machining technologies (turning x grinding) have almost the same Ra value. In a more detailed description of these surfaces, it is quite obvious that everyone is completely different and will behave quite differently in operation.

Acknowledgements

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