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DETERMINATION OF RELIABLE AREA SIZES FOR 3D ROUGHNESS MEASUREMENT

Abstract. *Surface roughness characterization plays an important role in the qualification of machined surfaces. As a result of the development of high resolution 3D scanning techniques, researchers and technologists have more possibilities to analyze surface topography in a more detailed way. The purpose of this study is determining the minimal measurement area size of surfaces hard machined by single-point and abrasive tools. Some important height parameters were analyzed:* S_a, S_q, S_p, S_v, S_{sk} *and* S_{ku}. *It was found that the minimum area sizes vary for the different roughness parameters, however, in several cases minimization is possible, depending on the purpose of the surface analytics.*

Keywords: *hard turning; grinding; polishing; 3D surface topography.*

1. INTRODUCTION

In the automotive industry, surface topography characterization and surface qualification have great importance. Not only the machined parts have to fulfill the quality requirements but also with the appearance of new materials the technologists have to improve the machining procedures and circumstances [1]. 2*D* surface measurement has been widely applied in the last several decades; however, mainly in technology development the application of 3*D* is increasingly widespread. 3*D* surface analysis provides more detailed and more exact information about the surfaces, which has a great importance e.g. in tribological characteristics of contact surfaces or fatigue characteristics [2].

The selection of measurement area size is an unsolvable problem in 3*D* surface topography analysis. There is no exact method that ensures the scanned area results in reliable parameter values or analytics [3]. At the same time, 3*D* surface scanning is a time-consuming and therefore relatively expensive process. This means that the designation of a minimum surface that produces reliable results is important [4].

There are many studies that prove that the unification of measurement and evaluation area is still not solved. Grzesik et al. [5] applied a 2.5 × 2.5 mm area size for hard turning. For the same machining technology studies for 0.8 × 0.8 [6] and 0.5 × 0.5 mm [7] area sizes can also be found. Similarly, for grinding 0.5 × 0.5 mm [7] and 2.5 × 2.5 mm [8] areas can be found. At the same time, not only squared areas are applied for measurement, but also rectangular ones for griding (e.g. [9, 10]. Squared 1.75 × 1.75 [11] and also rectangular 1.9 × 2.5 mm [12] areas were applied in polishing experiments. There is relatively high diversity in burnishing [5, 13], milling [14, 15] and in other technologies [16, 17] too.

Analyzing the different surface areas and the reliability of the measurements based on descriptive statistical methods seems a promising process for minimizing the scanned area size [18]. Molnar and Szabo suggested a simple method for determining this minimum in the case of different roughness parameters for hard turning and grinding [19].

In this paper this method is applied for the same two technologies but with different material and technological data. Additionally, the minimization method is applied for a polished surface.

In 3*D* surface topography characterization, some important surface height parameters were analyzed. The arithmetical (S_a) and root mean square height (S_q) are the first choices for judging the 'smoothness' of a surface. The 2*D* counterpart of the S_a parameter is widely applied in machining technology in part drawings and in academic studies, too. The 3*D* parameter S_a is widely used in scientific studies, e.g. for comparing theoretical and real roughness values [20] and analyzing the effects of technological parameters [21] or the effects of the cutting tool path on the topography features [22]. The maximum peak height (S_p), the maximum pit height (S_v), the kurtosis (S_{ku}) and the skewness (S_{sk}) parameters are determining parameters for the characterization of tribological behavior [23], including wear resistance [24, 25], fatigue strength or fluid-retention ability [26, 27].

2. APPLIED METHODS

In the experiments three surfaces were analyzed. One was hard turned, the other was ground after hard turning and the third was polished after hard turning.

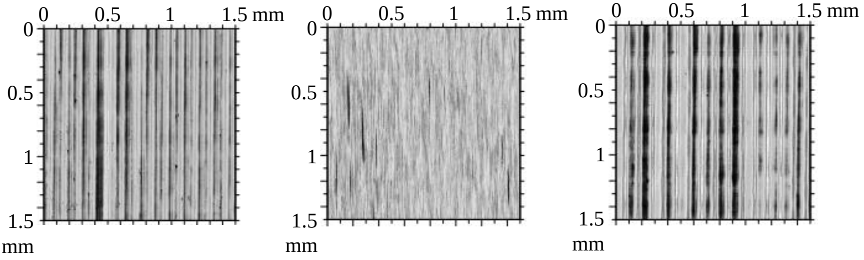
The hard turning was carried out on a CNC lathe type Optiturn S600. The applied insert was CNGA 120408 TA4. The cutting parameters were: cutting speed (v_c): 120 m/min; feed rate (f): 0.1 mm/rev; depth-of-cut (a_p): 0.2 mm. For grinding a CNC mantle grinder type Studer S31 was used. The grinding wheel speed (v_T) was 25 m/s, the workpiece rpm (n_W) was 600 1/min, the feed rate (f) was 700 mm/min, and the removed allowance (Z) was 0.005 mm. The diameter of the corundum wheel was 400 mm, and the grain size was 80 μm. For the polishing, a manual grinder type Bernardo DS200-400 was used. The polishing speed was 2850 1/min, the paste used was Diastar (diamond grit 5.5–8 μm).

The machined surfaces were external cylindrical surfaces with 50 mm diameter and 25 mm length, the material grade was AISI 4140, with hardness 53–54 HRC.

For the roughness measurement, a 3*D* roughness tester type AltiSurf 520 was used. The measured area was 1.75 × 1.75 mm, the side length of the evaluated area were 1.5 mm. The cutoff was 0.25 mm. The resolution of the optical sensor (type CL2) was 1 μm in *x* and y directions and 0.012 μm in *z* direction. The scanning speed was 1000 μm/s. For analyzing the different area sizes the highest area was scanned and smaller areas were then extracted from it. The difference in the side length of two consecutive areas was 0.1 mm. 14 areas were analyzed (side lengths from 0.2 to 1.5 mm). In this study an evaluation area was accepted as minimal if its roughness value does not exceed ±5% of a previously designated reference value.

3. RESULTS AND DISCUSSION

In Fig. 1 the analyzed surfaces are demonstrated. It can be observed that the ground surface (Fig 1b) is random, because the feed marks of the roughing (hard turning) are entirely removed by choosing a minimum allowance [28], and in the case of the polished surface (Fig. 1c) the feed marks of the previous (roughing) machining procedure can still be observed. The reason for this difference between the two abrasive finishing procedures is that in the case of grinding the size of the removed allowance is larger, while the manual polishing only improved some roughness parameter values.



a) b) c)

Figure 1 – Topography of the hard turned (a), ground (b) and the polished (c) surfaces

The 2*D* and 3*D* roughness parameter values were compared, from which it can be observed that there are relatively high differences between the corresponding values (Table 1). The 2*D* measurements were carried out at 1.25 mm evaluation length, and the 3*D* ones at 1.5 × 1.5 mm area.

The 3*D* parameters are considered reliable because the magnitude of the measured points is larger. In the case of hard turning and polishing the S_q and S_a parameters are 3.03–4.2% higher than their 2*D* counterparts. In the case of grinding the 3*D* values are lower by 4.67–7.03%. Concerning the S_p and S_v parameters, relatively high fluctuations were observed in the data: the 3*D* values are 4.83–18.42% higher that the R_p and R_v values obtained in the three analyzed machining technology. The skewness and kurtosis values are also fluctuating: the differences for hard turning, grinding and polishing (3*D* compared to the 2*D* parameter) are 0.44%, 8.85%, and -26.23%, respectively. These values for the kurtosis parameter are 2.28%, 14.04%, and 2.51%.

Table 1 – Comparison of the 2*D* and 3*D* roughness parameters

Roughness parameter	**Hard turning**		**Grinding**		**Polishing**	
	2*D*	3*D*	2*D*	3*D*	2*D*	3*D*
R_q / S_q	0.4738	0.4904	0.4094	0.3903	0.2216	0.2309
R_a / S_a	0.3597	0.3706	0.3298	0.3066	0.1919	0.1976
R_p / S_p	1.4114	1.5377	0.8183	0.8578	0.4416	0.4783
R_v / S_v	0.8179	0.8623	1.168	1.2926	0.3474	0.4114
R_{sk} / S_{sk}	1.0926	1.0974	-0.5243	-0.5707	0.3569	0.2633
R_{ku} / S_{ku}	3.8495	3.9373	2.9867	3.4060	1.9107	1.9586

In Figs. 2–7 the analyzed roughness values are plotted as a function of the evaluation area. The S_q and S_a values of the hard turned surface are similar when the side lengths of the evaluation area are between 0.6 and 1.5 mm, while on lower areas a deviation can be observed in the data (Fig. 2a). Concerning the S_p and S_v values for the same surface, low deviation of the values can be observed between 0.8 and 1.5 mm side lengths (Fig. 2b). Below this range the values show deviation, and between 0.2 and 0.5 mm side lengths: an increase and a decrease can be observed in the S_v and S_p data, respectively.

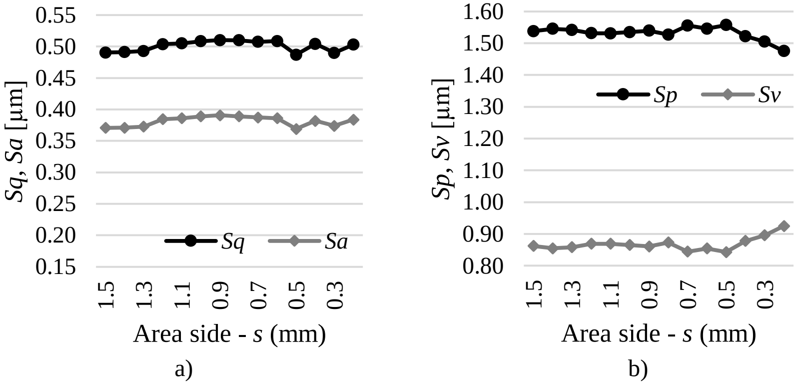
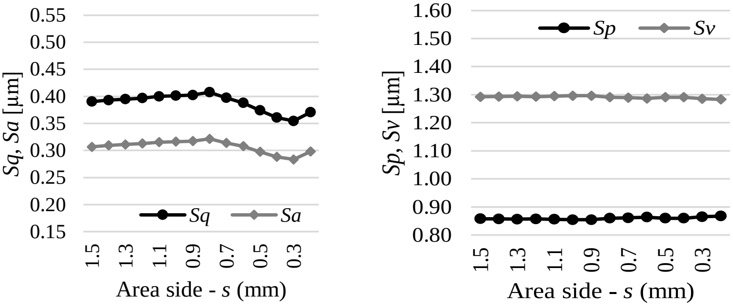


Figure 2 – S_q and S_a parameters (a) and S_p and S_v parameters (b) as a function of the area size for hard turned surface

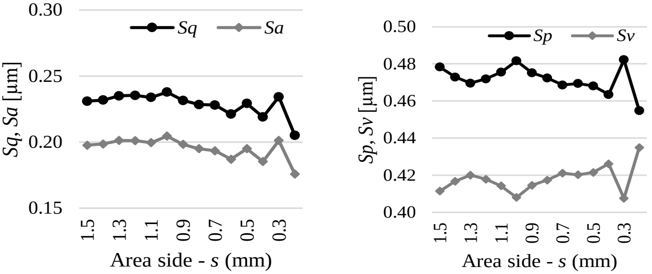
In the case of the ground surface the S_q and Sa data are relatively stable between 0.7 and 1.5 mm side lengths; however, both data are increasing slightly (Fig. 3a). Below these area sizes the parameters decrease and at the smallest analyzed area an outlying value is observed. Concerning the S_p and S_v values of the ground surface, both are stable at all area sizes (Fig. 3b).



a) b)

Figure 3 – The S_q and S_a parameters (a) and the S_p and S_v parameters (b) in function of the area size for ground surface

For the S_q and S_a values stable data were obtained between 1.1 and 1.5 mm side lengths (Fig. 4a). Below this area the values were decreased and between 0.2 and 0.6 mm increasing deviations were observed. The S_p and S_v values of the polished surface are not stable on the whole range (Fig. 4b). By decreasing the evaluation area, first a decrease, then an increase can be observed in the S_p values. Between 0.4 and 1 mm side lengths the values decrease again, and below this range a deviation is observed. The reason for the relatively high deviation is that the polishing was preceded by hard turning, and the height distribution is influenced by both the hard turning and the abrasive machining.



a) b)

Figure 4 – S_q and S_a parameters (a) and the S_p and S_v parameters (b) as a function of the area size for polished surface

This phenomenon draws the attention that the S_a parameter, which indicates improvement of the polished surface compared to the hard turned and ground ones, is not enough to characterize the surface in a detailed manner. The tendencies of the S_v values are the opposite of those of the S_p values. The reason for this is that the maximum height (S_z), which is the sum of S_p and S_v, is constant at all the analyzed area sizes. This is valid for all three analyzed surfaces. The S_z values for the hard turned, ground and polished surface at 1.5 × 1.5 mm evaluation area are 2.40, 2.15, and 0.89, respectively.

The skewness (S_{sk}) and the kurtosis (S_{ku}) are the higher moments of the height distribution of a surface. They are determinant parameters from the tribological point of view; however, they are sensitive to extreme peaks and valleys, and behave differently when cutting procedures are compared. This can be observed in the S_{ku} values of the hard turned surface (Fig. 5). The topography is periodic, and due to the characteristics of hard machining the distribution of sharp peaks varies throughout the analyzed area. At large areas (1.3–1.5) its values are high, but on smaller are sizes first a decrease, then an increase, and between 0.2 and 0.5 mm side lengths a relatively high deviation can be observed. In contrast, the S_{sk} values are relatively stable; the highest values were obtained between area sizes 1.3 × 1.3 and 1.5 × 1.5 mm.

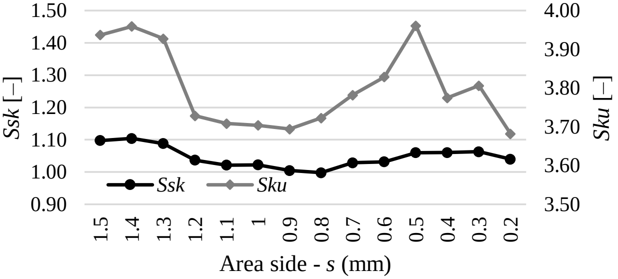


Figure 5 – S_{sk} and S_{ku} parameters as a function of the area size for hard turned surface

Analyzing the ground surface, where height distribution is random, the S_{ku} and S_{sk} values are relatively stable between 0.8 and 1.5 mm side lengths (Fig. 6). Below this range a decrease is obtained in the S_{ku} and an increase in the S_{sk} values.

The S_{sk} parameter of the polished surface show a considerable decrease between side lengths 0.4 and 1.5 mm, while the S_{ku} parameter shows a considerable deviation between 0.2 and 1.1 mm (Fig. 7). The reason for the relatively high deviation is the above-mentioned complexity of the topography (polishing after hard turning).

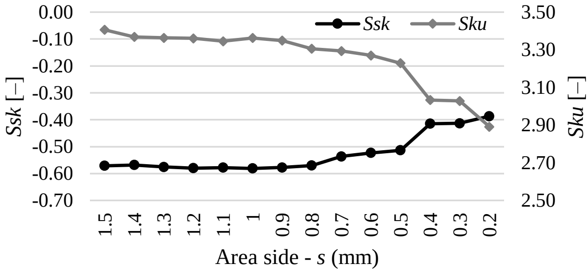


Figure 6 – S_{sk} and S_{ku} parameters as a function of the area size for ground surface

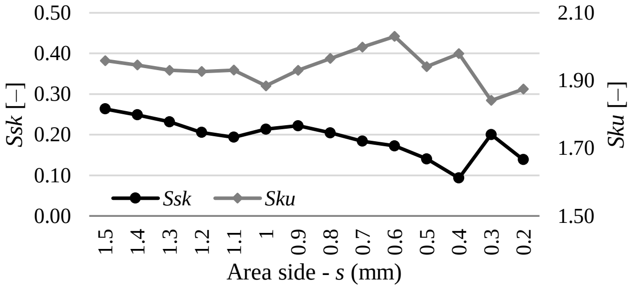


Figure 7 – S_{sk} and S_{ku} parameters as a function of the area size for polished surface

Applying the evaluation area minimization method, the parameter values obtained at the highest evaluation area (basis value) were considered reliable and a ±5% difference range was designated. The minimum area was the smallest at which a parameter value does not exceed this limit. In Table 2 the basis value, the ±5% limit (acceptance range), the first not acceptable value, and the acceptable roughness value and the corresponding area size are summarized. For the hard turned surface, the S_q, S_p and S_v parameter values at relatively small areas (0.2–0.3 mm side length) are similar to those obtained at 1.5 × 1.5 mm. The S_{sk} and S_{ku} parameters can be considered reliable at 1.3 × 1.3 mm or larger areas. A ground surface is random, i.e. the height distribution is closer to normal and the feed marks do not influence the topography as much as in the case of hard turning. The S_p and S_v values can be evaluated reliably at 0.2 mm side length areas, while the minimum area for S_q and S_a mean height parameters is 0.5 × 0.5 mm. In the case of the S_{sk} and S_{ku} parameters the minimum area is lower than that of hard turning: 0.6–0.8 mm side length. Similar area sizes were obtained for polishing in the cases of S_q, S_a,

S_p and S_v. The minimum side length of the area for S_q and S_a is 0.5–0.7 mm and for S_p and S_v 0.2–0.3 mm. The S_{sk} and S_{ku} parameters, however, cannot be compared well to those of the other two procedures. The minimum side length for the S_{sk} is 1.5 mm and for the S_{ku} is 0.4 mm.

Table 2 – Determination of the minimal area size

Roughness parameter	Roughness value at 1.5 × 1.5 mm	Acceptance range (± 5%)		Rejected value	Accepted value	Accepted area (mm^2)
Hard turning						
S_q	0.490	0.466	0.515	–	0.503	0.2×0.2
S_a	0.371	0.352	0.389	0.391	0.389	1×1
S_p	1.538	1.461	1.615	–	1.475	0.2×0.2
S_v	0.862	0.819	0.905	0.925	0.896	0.3×0.3
S_{sk}	1.097	1.043	1.152	1.037	1.088	1.3×1.3
S_{ku}	3.937	3.740	4.134	3.728	3.928	1.3×1.3
Grinding						
S_q	0.390	0.371	0.410	0.361	0.374	0.5×0.5
S_a	0.307	0.291	0.322	0.288	0.298	0.5×0.5
S_p	0.858	0.815	0.901	–	0.867	0.2×0.2
S_v	1.293	1.228	1.357	–	1.283	0.2×0.2
S_{sk}	-0.571	-0.542	-0.599	-0.536	-0.570	0.8×0.8
S_{ku}	3.406	3.236	3.576	3.229	3.270	0.6×0.6
Polishing						
S_q	0.231	0.219	0.242	0.219	0.229	0.5×0.5
S_a	0.198	0.188	0.207	0.187	0.193	0.7×0.7
S_p	0.478	0.454	0.502	–	0.455	0.2×0.2
S_v	0.411	0.391	0.432	0.435	0.408	0.3×0.3
S_{sk}	0.263	0.250	0.276	0.249	0.263	1.5×1.5
S_{ku}	1.959	1.861	2.057	1.841	1.979	0.4×0.4

4. CONCLUSIONS

Three surfaces finished by different machining procedures (hard turning, grinding and polishing) were analyzed. The findings of the applied minimization method are the following.

- For the S_a and S_q parameters the minimum evaluation areas vary depending on the applied machining procedure. When analyzing S_q the side length of this area is 0.2 mm but 1 mm when analyzing S_a for hard turned surfaces. The minimum side lengths are 0.5 and 0.7 mm for ground and polished surfaces, respectively.
- In the cases of the S_p and S_v parameter a side length of 0.3 mm is recommended for the minimum area in all three analyzed procedures.

- In the cases of the S_{sk} and S_{ku} parameters the minimum area sizes strongly vary in the three procedures. Due to the purely random feature of the ground surface, its minimum area is relatively low: 0.8 × 0.8 mm.

These statements are valid for the three procedures and within the applied cutting data and technology parameters.

References: **1.** *Nagy, A., Kundrak, J.:* Changes in the values of roughness parameters on face-milled steel surface, Rezanie i Instrumenty v Tekhnologicheskih Sistemah 92, pp.85-95, 2020. **2.** *Zaghal, J., Mertinger, V., Filep, A., Varga, G., Benke, M.:* Characterization of residual stresses induced into bearing rings by means of turning in soft state using different turning parameters, Journal of Machine Engineering 21(4), pp.49-56, 2021. **3.** *Yong, Q., Chang, J., Liu, Q., Jiang, F., Wei, D., Li, H.:* Matt polyurethane coating: Correlation of surface roughness on measurement length and gloss, Polymers 12, paper 326, 2020. **4.** *Molnar, V.:* Minimization method for 3D surface roughness evaluation area, Machines 9, paper 192, 2021. **5.** *Grzesik, W., Rech, J., Zak, K.:* High-precision finishing hard steel surfaces using cutting, abrasive and burnishing operations, Procedia Manufacturing 1, pp.619–627, 2015. **6.** *Matras, A., Zębala, W., Machno, M.:* Research and method of roughness prediction of a curvilinear surface after titanium alloy turning, Materials 12, paper 502, 2019. **7.** *Grzesik, W., Zak, K., Kiszka, P.*: Comparison of surface textures generated in hard turning and grinding operations, Procedia CIRP 13, pp.84–89, 2014. **8.** *Legutko, S., Zak, K., Kudlacek, J.:* Characteristics of geometric structure of the surface after grinding, MATEC Web Conf. 94, paper 02007, 2017. **9.** *Wojciechowski, S., Twardowski, P., Chwalczuk, T.:* Surface roughness analysis after machining of direct laser deposited tungsten carbide, Journal of Physics: Conf. Ser. 483, paper 012018, 2014. **10.** *Schmahling, J., Hamprecht, F.A., Hoffmann, D.M.P.:* A three-dimensional measure of surface roughness based on mathematical morphology. Technical Report from Multidimensional Image Processing, IWR; University of Heidelberg, Germany, 2006. **11.** *Zhou, J., Han, X., Li, H., Liu, S., Shen, S., Zhou, X., Zhang, D.:* In-situ laser polishing additive manufactured AlSi10Mg: Effect of laser polishing strategy on surface morphology, roughness and microhardness, Materials 14, paper 393, 2021. **12.** *Zhou, H., Zhou, H., Zhao, Z., Li, K., Yin, J.:* Numerical simulation and verification of laser-polishing free surface of S136D die stee**l**, Metals 11, paper 400, 2021. **13.** *Dzierwa, A., Markopoulos, A.P.:* Influence of ball-burnishing process on surface topography parameters and tribological properties of hardened steel, Machines 7, paper 11, 2019. **14.** *Nadolny, K., Kaplonek, W.:* Analysis of flatness deviations for austenitic stainless-steel workpieces after efficient surface machining, Measurement Science Reviev 14, paper 204, 2014. **15.** *Kundrak, J., Nagy, A., Markopoulos, A.P., Karkalos, N.E.:* Investigation of surface roughness on face milled parts with round insert in planes parallel to the feed at various cutting speeds, Rezanie i Instrumenty v Tekhnologicheskih Sistemah 91, pp.87–96, 2019. **16.** *Karolczak, P., Kowalski, M., Wisniewska, M.:* Analysis of the possibility of using wavelet transform to assess the condition of the surface layer of elements with flat-top structures, Machines 65, paper 8, 2020. **17.** *Deltombe, R., Kubiak, K.J., Bigerelle, M.:* How to select the most relevant 3D roughness parameters of a surface?, Scanning 36, pp.150–160, 2014. **18.** *Molnar, V.:* Designation of evaluation area in measuring 3d surface roughness, Rezanie i Instrumenty v Tekhnologicheskih Sistemah 93, pp.56-64,2020. **19.** *Molnar, V., Szabo, G.:* Designation of minimum measurement area for the evaluation of 3D surface texture, Journal of Manufacturing Processes 83, pp.40-48, 2022. **20.** *Kundrak, J., Felho, Cs., Nagy, A.*: Analysis and prediction of roughness of face milled surfaces using CAD model, Manufacturing Technology 22(5), pp.558-572, 2022. **21.** *Ferencsik, V., Varga, G.:* The influence of diamond burnishing process parameters on surface roughness of low-alloyed aluminium workpieces, Machines 10(7), paper 564, 2022. **22.** *Kundrak, J., Nagy, A., Markopoulos, A.P., Karkalos, N.E., Skondras-Giousios, D.:* Experimental study on surface roughness of face milled parts with round insert at various feed rates, Rezanie i Instrumenty v Tekhnologicheskih Sistemah 92, pp.96-106, 2020. **23.** *Ferencsik, V., Varga, G.:* The effect of burnishing process on skewness and kurtosis of the scale limited surface, Rezanie i Instrumenty v Tekhnologicheskih Sistemah 97, pp.83-90, 2022. **24.** *Molnar, V., Sztankovics, I.:*

Analysis of roughness parameters determining tribological properties in hard turned surfaces, Hungarian Journal of Industry and Chemistry 49(2), pp.77-84, 2021. **25.** *Zhu, X., Dong, Z., Zhang, Y., Cheng, Z.:* Fatigue Life Prediction of Machined Specimens with the Consideration of Surface Roughness, Materials 14, paper 5420, 2021. **26.** *Gapinski, B., Firlik, B., Mathia, T.G.:* Characteristics of tram wheel wear: Focus on mechanism identification and surface topography, Tribology International 150, paper 106365, 2020. **27.** *Molnar, V.:* Tribological properties and 3D topographic parameters of hard turned and ground surfaces, Materials 15(7), paper 2505, 2022. **28.** *Kundrak, J., Deszpoth, I., Molnar, V.:* Increasing productivity of combined procedure by reducing grinding allowance, Rezanie i Instrumenty v Tekhnologicheskih Sistemah 90, pp.26-35, 2019.

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ВИЗНАЧЕННЯ НАДІЙНИХ РОЗМІРІВ ОБЛАСТІ ДЛЯ 3*D* ВИМІРЮВАННЯ ШОРСТКОСТІ

Анотація. *Характеристика шорсткості поверхні відіграє важливу роль у кваліфікації оброблених поверхонь. У результаті розробки методів 3D-сканування з високою роздільною здатністю дослідники та технологи мають більше можливостей для більш детального аналізу топографії поверхні. Метою даного дослідження є визначення мінімального розміру площі вимірювання поверхонь, оброблених одноточковим та абразивним інструментом. Було проаналізовано деякі важливі параметри висоти:* S_a, S_q, S_p, S_v, S_{sk} *та* S_{ku}. *Було виявлено, що мінімальні розміри площі різняться для різних параметрів шорсткості, однак у деяких випадках можлива мінімізація, залежно від мети аналізу поверхні. Вибір розміру зони вимірювання є нерозв'язною проблемою в 3D-аналізі топографії поверхні. Немає точного методу, який би гарантував, що відсканована область дасть надійні значення параметрів або аналітику. У той же час 3D-сканування поверхні є трудомістким і тому відносно дорогим процесом. Це означає, що визначення мінімальної поверхні, яка дає надійні результати, є важливим. Для вимірювання шорсткості використовувався тривимірний тестер шорсткості типу AltiSurf 520. Виміряна площа становила 1,75 × 1,75 мм, довжина сторони оцінюваної області становила 1,5 мм. Границя становила 0,25 мм. Роздільна здатність оптичного датчика (типу CL2) становила 1 мкм у напрямках x та y та 0,012 мкм у напрямку z. Швидкість сканування становила 1000 мкм/с. Для аналізу різних розмірів області була відсканована найвища область, а потім з неї вилучено менші області. Різниця в довжині сторін двох послідовних ділянок становила 0,1 мм. Проаналізовано 14 ділянок (довжина сторін від 0,2 до 1,5 мм). У цьому дослідженні площа оцінки була прийнята як мінімальна, якщо її значення шорсткості не перевищує ±5% від попередньо визначеного контрольного значення. Було проаналізовано три поверхні, оброблені різними процедурами механічної обробки (жорсте точіння, шліфування та полірування). Для параметрів* S_a *і* S_q *мінімальна площа оцінки змінюється в залежності від застосовуваної процедури обробки. При аналізі* S_q *довжина сторони цієї області становить 0,2 мм, та 1 мм при аналізі* S_a *для точених поверхонь. Мінімальна довжина сторін становить 0,5 і 0,7 мм для шліфованих і полірованих поверхонь відповідно. У випадку параметрів* S_p *і* S_v *рекомендована довжина сторони 0,3 мм для мінімальної площі в усіх трьох аналізованих процедурах. У випадку параметрів* S_{sk} *і* S_{ku} *мінімальні розміри області сильно відрізняються в трьох процедурах. Через чисто випадкову особливість поверхні ґрунту її мінімальна площа відносно мала: 0,8 × 0,8 мм. Ці твердження дійсні для трьох процедур і в межах застосовуваних даних різання та параметрів технології.*

Ключові слова: *жорстке точіння; шліфування; полірування; 3D рельєф поверхні.*