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ROUNDNESS ERROR AND TOPOGRAPHY OF HARD TURNED SURFACES

Abstract. *Accuracy and topography are significant indicators of precision machined high-quality surfaces. Case hardened steel (16MnCr5) was analyzed to obtain information about the effects of technological data and the connections between the analyzed accuracy (roundness) and roughness parameters (S_a, S_z, S_{sk}, S_{ku}). It was found that the feed rate has a significant influence on the roundness and the roughness parameters, and there are strong relationships between the roundness and these roughness parameter values: the correlation coefficients varied between 0.78 and 0.85.*

Keywords: *roundness; 3D surface topography; hard turning; precision machining.*

1. INTRODUCTION

Several types of machined components are built into units or products where they must fulfill numerous requirements concerning the functionality and lifetime. The purpose of precision machining is ensuring the accuracy of these components and the quality of their surfaces [1]. Although additive manufacturing has been in the focus of research in recent years by endeavoring to increase accuracy, also conventional technologies face challenges due to the new materials [2], cutting tool materials [3] and special technologies [4, 5].

Accuracy is an important characteristic of a machined component, because it affects the durability and assembly of the parts [6, 7]. At the same time, surface quality, such as surface layer characteristics [8], texture, roughness or stress state, also play an important role in the lifetime of a component [9].

Numerous studies have been published in the topic of machined part accuracy; among others they focus on the optimization of machining parameters [7], the effect of coolant material [10], the simulation of uncertainties [11, 12] or the application of artificial intelligence [13, 14]. Concerning surface roughness topics, the most focused-on topics are the cutting data selection for optimizing the roughness parameter values [15, 16], roughness prediction [17, 18], comparison of machining technologies [19, 20], tribological effects of surface quality [21, 22], cutting conditions [23, 24] or the analysis of measurement methods [25, 26].

In precision machining not only abrasive but also single-point-tools are applied to ensure the same surface quality. However, from a surface functional point of view it has to be considered whether a periodic or a random topography is needed [27]. Several studies report about the applicability of one or the other procedure [28, 29] or about comparative results for hard turning and grinding [30] based on surface quality considerations.

In this study hard turned surfaces are analyzed from an accuracy and surface quality point of view based on some widely applied qualification parameters. Roundness and topography measurements were carried out and compared to obtain information about the effects of cutting parameters. In the experiment 16MnCr5 case hardened steel was applied, which is widely used in the automotive industry. 3*D* topography analysis was applied to obtain exact information about the surface quality [31]. The experiment was carried out based on factorial experiment design and basic statistical indicators were calculated to understand the relationship between the roundness and the analyzed roughness parameters in detailed manner.

2. EXPERIMENTAL METHODS

The hard turning experiment was carried out on the machine tool EMAG VSC400 DDS. The applied tool holder and the CBN insert were PCLNR 2020-K12 and CNGA 120408, respectively. The cutting parameters were:

- a_p (depth-of-cut): 0.05 and 0.35 mm;
- v_c (cutting speed): 120 and 240 m/min;
- f (feed rate): 0.04 and 0.2 mm/rev.

The machining was carried out in all combinations of the parameter values (two values per parameter), which resulted in eight different setups. The machined material was 16MnCr5, and Ø60 mm surfaces were hard turned. The hardness of the material was between 60 and 63 HRC.

The roughness measurement was carried out on a 3*D* topography tester equipment Altisurf 520. For the topography scanning (CL2) an optical sensor was used. The resolution of the sensor in x, y and z directions was 1, 1, and 0.012 µm, respectively. The squared evaluation areas of the surfaces were 4 mm^2. Two cut-off lengths were applied because of the periodicity differences of the machined surfaces: 0.08 and 0.8 mm. The preparation of scanned surfaces included form removal, Gauss filtering and thresholding of the extreme peaks and valleys. In Eqs 1–4 the analyzed roughness parameters are defined: S_a – arithmetical mean height; S_z – maximum height; S_{sk} – skewness; S_{ku} – kurtosis.

$$Sa = \frac{1}{A}\iint_{A} |Z(x,y)|\,dx\,dy \tag{1}$$

$$Sz = \max_{A} Z(x,y) + \left|\min_{A} Z(x,y)\right| \tag{2}$$

$$Ssk = \frac{1}{Sq^3}\left[\frac{1}{A}\iint_{A} Z^3(x,y)\,dx\,dy\right] \tag{3}$$

$$Sku = \frac{1}{Sq^4}\left[\frac{1}{\mathrm{A}}\iint_{\mathrm{A}} Z^4(x,y)\,dx\,dy\right] \qquad (4)$$

The roundness error measurement was carried out on the shape and position accuracy measuring equipment Talyrond 365. The scanning speed was 6 mm/s, the scaling was 1 µm/div. For the analysis the minimum zone type reference circle method was applied. The applied filter was Gauss filter, and the filtering range was 1–500 upr.

3. RESULTS AND DISCUSSION

The machined surfaces were analyzed based on widely used roughness data. The roundness error has high importance in qualifying the accuracy of cylindrical surfaces. In Table 1 the cutting and the measurement data of the analyzed surfaces are summarized.

Table 1 – Cutting data and measurement data of the machined surfaces

Surface	a_p	v_c	f	S_a	S_z	S_{sk}	S_{ku}	*RONt*
A	0.05	120	0.04	0.11	0.81	-0.05	3.27	0.99
B			0.2	1.21	5.16	0.64	2.22	1.63
C		240	0.04	0.15	1.04	-0.01	3.15	0.57
D			0.2	1.22	5.17	0.64	2.16	1.63
E	0.35	120	0.04	0.25	1.87	-0.05	3.27	1.5
F			0.2	1.18	5.17	0.71	2.35	1.76
G		240	0.04	0.24	1.73	0.02	3.17	0.6
H			0.2	1.18	5.23	0.63	2.22	1.96

3.1. Analysis of the roughness values

In Fig. 1 the roughness values of the surfaces are presented. Analyzing the effects of the cutting data on the roughness values, the following can be stated.

The A, C, E, G surfaces are machined at the lower feed rate, and the values of S_a and S_z are significantly lower than those belonging to the surfaces machined at the higher feed rate. The cutting speed and the depth-of-cut do not influence these values. The same can be observed in the skewness values: the height distribution of the A, C, E and G surfaces indicate normal distribution by their S_{sk} values around 0. The B, D, F and H surfaces are asymmetric, they are less filled in the peak zone, which means that their wear resistance and load-bearing capacity are lower. Concerning the kurtosis values, those of the surfaces machined at the lower feed rate indicate normal distribution by their S_{ku} values around 3. The surfaces machined at the higher feed rate incorporate fewer sharp peaks and valleys, therefore, e.g. their fluid-retention abilities are worse. Neither the cutting speed nor the depth-of-cut have an influence on these two topography parameters.

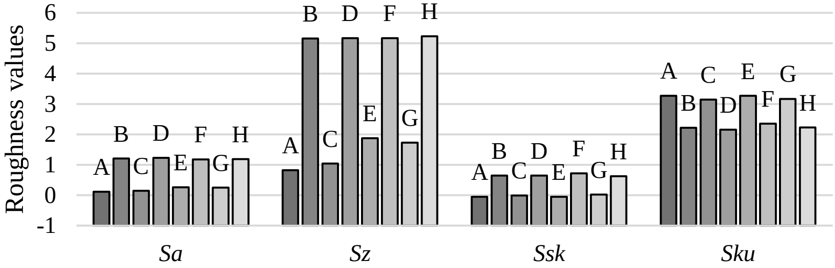


Figure 1 – Roundness values of the machined surfaces

3.2. Analysis of the roundness values

Analyzing the effects of cutting data on the roundness, the following observations can be made (Fig. 2): at the low feed rate the roundness error decreased by 40–58% when the cutting speed was increased. This connection was not observed at the higher feed rate. When the depth-of-cut increased, all the roundness data increased by 5–52%.

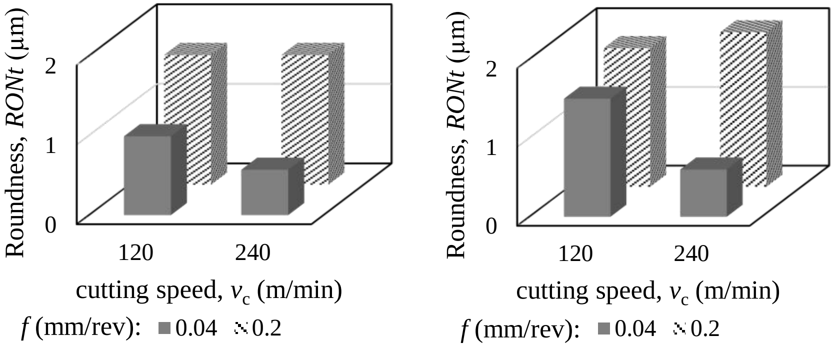
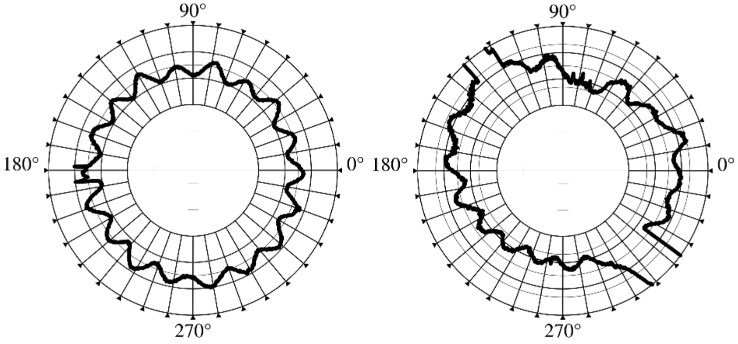


Figure 2 – Roundness values of the different setups

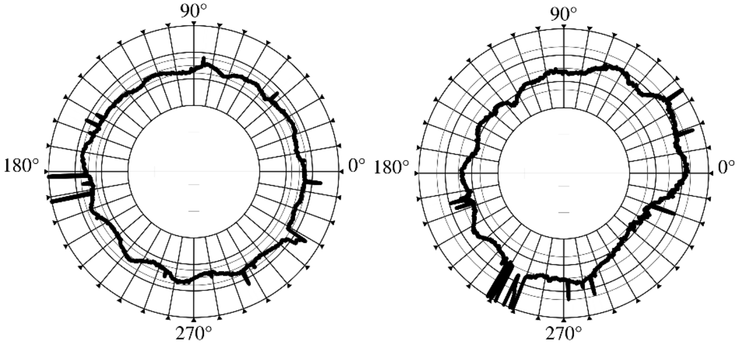
In Figs. 3–6 the roundness diagrams are demonstrated. At low depth-of-cut (a_p = 0.05 mm), cutting speed (v_c = 120 m/min) and feed rate (f = 0.04 mm/rev) the roundness error is relatively low and the surface (A) includes no unmeasured points or ranges that result from extreme peaks (Fig 3a). At the higher feed rate (f = 0.2 mm/rev), the number of these outliers of the surface points (B) increased and a certain level of roundness was obtained (Fig 3b), which increased the roundness value by 65%.



a) b)

Figure 3 – Roundness of surface A (a) and B (b)

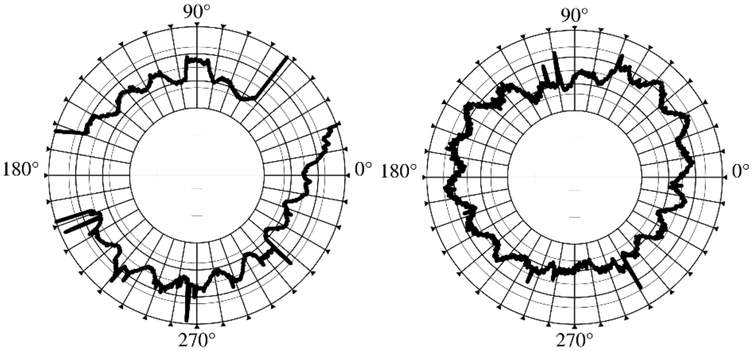
At the higher cutting speed (v_c = 240 m/min) and low depth-of-cut the irregularities of the surface (C and D) increased (Fig 4) and ovality was obtained at the surface (D) machined by the higher feed rate (Fig 4b). These resulted in the increase of roundness by 186%.



a) b)

Figure 4 – Roundness of surface C (a) and D (b)

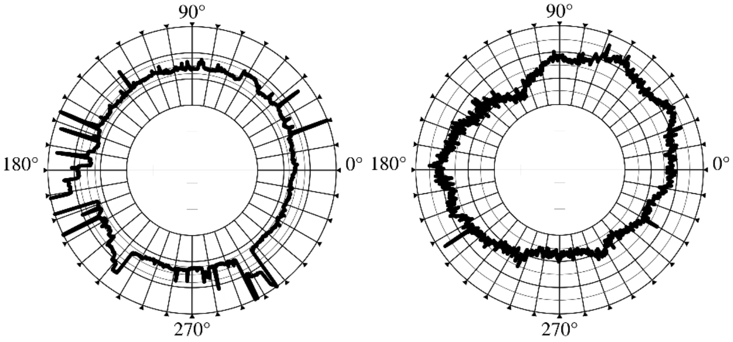
At the higher depth-of-cut (a_p = 0.35 mm) and lower cutting speed more outliers were obtained for the surface (E) machined by lower feed rate (Fig 5a). However, the ovality can be observed on the surface (F) machined by the higher feed rate, which resulted in a 17% increase in the roundness (Fig 5b).



a) b)

Figure 5 – Roundness of surface E (a) and F (b)

Similar phenomena can be observed at the surfaces machined at the higher depth-of-cut and cutting speed. The surface machined at the lower feed rate (G) has more outliers (Fig 6a), and the one (H) machined at the higher feed rate has a higher ovality (Fig 6b), which resulted in 227% higher roundness.



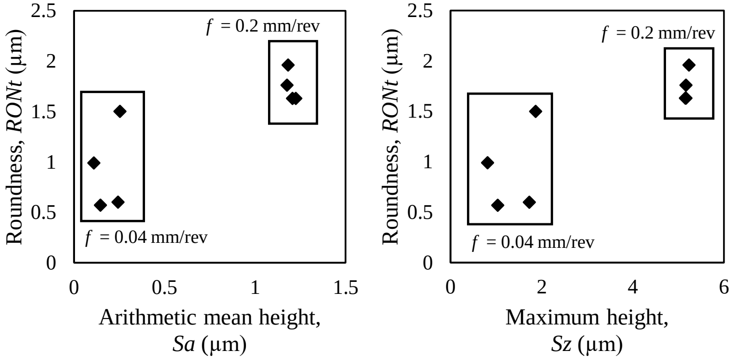
a) b)

Figure 6 – Roundness of surface G (a) and H (b)

3.3. Connections between the roughness and roundness values

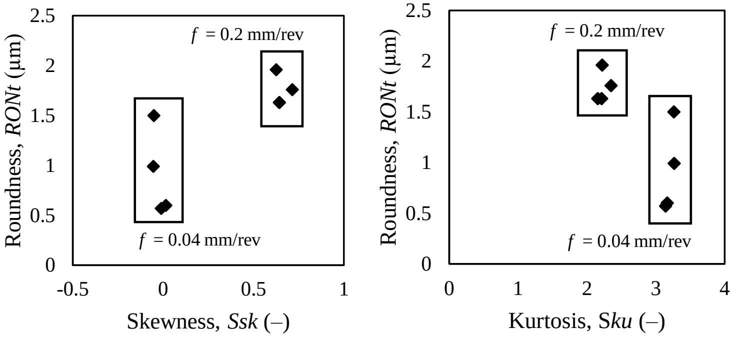
In Figs. 7 and 8 the connections between the measured roundness values and each roughness parameter are demonstrated and the separated groups of the results at different feed rates can be observed clearly.

The mean values of the S_a parameter at the lower and higher feed rates are 0.19 and 1.20 µm, respectively (Fig. 7a). The standard deviation values are 0.07 and 0.02 µm, the former can be considered high (relative deviation is 38%). The mean values of the S_z parameter are 1.36 and 5.18 µm at the lower and the higher feed rates, respectively (Fig. 7b). Here, the standard deviations are 0.52 and 0.03 µm, and the former can be considered high (relative deviation is 38%).



a) b)

Figure 7 – The roundness and the S_a (a) and S_z (b) values



a) b)

Figure 8 – The roundness and the S_{sk} (a) and S_{ku} (b) values

The mean values of the skewness are -0.03 and 0.66, and the standard deviations are 0.03 and 0.04 at the lower and the higher feed rates, respectively (Fig. 8a). The mean values of the kurtosis are 3.21 and 2.24, and the standard deviations are 0.06 and 0.08 at the lower and higher feed rates, respectively (Fig. 8b). The deviations can be considered low in the case of these two parameters.

The mean values of the roundness are 0.92 and 1.75 μm, and the standard deviations are 0.43 and 0.16 at the lower and higher feed rates, respectively. In the former case the relative deviation is relatively high: 47%.

The correlation (r) between the corresponding parameter pairs were analyzed. The correlation between S_a and the roundness is 0.83 and between S_z and the roundness is 0.85. These indicate not extremely, but strong relationships. These values for the skewness and kurtosis are 0.80 and 0.78, respectively. These indicate slightly weaker but still strong relationships.

The reason for the obtained connections between the roughness and roundness parameters is that at higher feed rate the analyzed roughness parameter values can be separated from each other, and meanwhile the higher feed rate results in higher cutting forces, which cause the deformation of the surface (ovality) or extremely outlying peaks or areas in the surface texture.

4. SUMMARY

Based on a machining experiment (hard turning) and roundness and roughness (S_a, S_z, S_{sk}, S_{ku}) measurements, the effects of the cutting data on the measured parameters were analyzed, and the connections between the roughness and the roundness data were compared. The findings can be interpreted for hard turning and in the analyzed parameter range (a_p = 0.05–0.35 mm; v_c = 120–240 m/min; f = 0.04–02. mm/rev). The main findings are the following:

- The measured S_a and S_z values obtained at the 0.04 mm/rev feed rate are lower than those obtained at 0.2 mm/rev, which strengths the findings of several earlier studies.
- The roundness error of hard turned surfaces is higher if higher feed rate or depth-of cut is applied. The increased error results from the ovality and/or the extreme outliers of the machined surface.
- There are strong relationships (high correlation coefficient) between the analyzed roughness and the roundness values: r = 0.78–0.85.

The limitation of the study is that the machining was carried out in only 8 parameter combinations. More refined results can be obtained by applying more (3 or 4) levels of the cutting data.

References: **1.** *Kundrak, J., Mamalis, A.G., Molnar, V.:* The efficiency of hard machining processes, Nanotechnology Perceptions 15, pp. 131–142, 2019. **2.** *Turmanidze, R., Popkhadze, G., Inasharidze, K.:* Improving the performance characteristics of human hip-joint implants by increasing the quality of processing and geometric accuracy of their spherical surfaces, Cutting and Tools in Technological System 93, pp. 103–113, 2020. **3.** *Kovalev, V., Klymenko, G., Vasylchenko, Y., Shapovalov, M., Antsiferova, O., Maiskykh, I.:* Results of industrial testing of carbide cutting tools by pulsed magnetic field treatment and the effect on the increase of the cutting process efficiency, Cutting and Tools in Technological System 95, pp. 3–12, 2021. **4.** *Bartarya, G., Choudhury, S.K.:* State of the art in hard turning, International Journal of Machine Tools and Manufacture 53(1), pp. 1–14, 2012. **5.** *Kvasnova, P., Kucerka, M., Hruby, D., Novak, D., Novak, V.:* Hardness tests and dimensional and shape precision analysis of construction and agricultural machinery components, Manufacturing Technology 18(6), pp. 943–949, 2018. **6.** *Fedorovich,V., Pyzhov, I., Ostroverkh, Y., Pupan, L., Garachenko, Y.:* Methodology for developing an expert system for the grinding of superhard materials, Cutting and Tools in Technological System 96, pp. 82–88, 2022. **7.** *Sumesh, C.S., Akbar, D.S., Purandharadass, H.S., Chandrasekaran, R.J.:* Optimization of dimensional tolerances and material removal rate in the orthogonal turning of AISI 4340 **steel**, Periodica Polytechnica Mechanical Engineering, 65(3), pp. 205–216, 2021. **8.** *Alok, A., Das, M.:* White layer analysis of hard turned AISI 52100 steel with the fresh tip of newly developed HSN2 coated insert, Journal of Manufacturing Processes 46, pp. 16–25, 2019. **9.** *Chen, L., Tai, B. L., Chaudhari, R. G., Song, X., Shih, A. J.:* Machined surface temperature in hard turning, International Journal of Machine Tools and Manufacture 121, pp. 10–21, 2017. **10.** *Jirapattarasilp, K., Kuptanawin, C.:* Effect of turning parameters on roundness and hardness of stainless steel: SUS 303, AASRI Procedia 3, pp. 160–165, 2012. **11.** *Binali, R., Kuntoglu, M., Pimenov, D.Y., Usca, U.A., Gupta, M.K., Korkmaz, M.E.***:** Advance monitoring of hole machining operations via intelligent measurement systems: A critical review and future trends, Measurement 201, art no 111757, 2022. **12.** *Varatharajulu, M., Duraiselvam, M., Kumar, M.B., Jayaprakash, G., Baskar, N.:* Multi criteria decision making through TOPSIS and COPRAS on drilling parameters of magnesium AZ91, Journal of Magnesium Alloys 10, pp. 2857–2874, 2021. **13.** *Du, C., Ho, C.L., Kaminski, J.:* Prediction of product roughness, profile, and roundness using machine learning techniques for a hard turning process, Advances in Manufacturing 9, pp. 206–215, 2021. **14.** *Zolpakar, N.A., Yasak, M.F., Pathak, S.:* A review: use of evolutionary algorithm for optimisation of machining parameters, The International Journal of Advanced Manufacturing Technology 115, pp. 31–47, 2021. **15.** *Cardoso, L.G., Madeira, D.S., Ricomini, T.E., Miranda, R.A., Brito, T.G., Paiva, E.J.:* Optimization of machining parameters using response surface methodology with desirability function in turning duplex stainless steel UNS S32760, The International Journal of Advanced Manufacturing Technology 117, pp. 1633–1644, 2021. **16.** *Bartarya, G., Choudhury, S. K.:* Effect of cutting parameters on cutting force and surface roughness during finish hard turning AISI52100 grade steel, Procedia CIRP 1, pp. 651–656, 2012. **17.** *Ozel, T., Karpat, Y.:* Predictive modeling of surface roughness and tool wear in hard turning using regression and neural networks, International Journal of Machine Tools and Manufacture 45, pp. 467–479, 2005. **18.** *Rehor, J., Fulemova, J., Kutlwaser, J., Gombar, M., Harnicarova, M., Kusnerova, M., Vagaska, A., Povolny, M., Valicek, J., Zatloukal, T.:* ANOVA analysis for estimating the accuracy and surface roughness of precisely drilled holes of steel 42CrMo4 QT, The International Journal of Advanced Manufacturing Technology 126, pp. 675–695, 2023. **19.** *Kundrak, J., Molnar, V., Deszpoth, I.:* Comparative analysis of machining procedures, Machines 6(2), art no 13, 2018. **20.** *Grzesik, W., Zak, K., Kiszka, P.:* Comparison of surface textures generated in hard turning and grinding operations, Procedia CIRP 13, pp. 84–89, 2014. **21.** *Molnar V.:* Tribological properties and 3D topographic parameters of hard turned and ground surfaces, Materials 15(7), art no 2505, 2022. **22.** *Molnar V.:* Asymmetric height distribution of surfaces machined by hard turning and grinding, Symmetry 14(8), art no 1591, 2022. **23.** *Poulachon, G., Moisan, A. L.:* Hard turning: chip formation mechanisms and metallurgical aspects, Journal of Manufacturing Science and Engineering 122(3), pp. 406–412, 2000. **24.** *Farsky, J., Baksa, T., Zetek, M.:* Grinding of maraging steel 1.2709 with SiC grinding wheels and effect of grinding conditions on the surface roughness and wear of the wheels, Manufacturing Technology 20(1), pp. 18–22, 2020. **25.** *Pytlak, B.:* The roughness parameters 2D and 3D and some characteristics of the machined surface topography after hard turning and grinding of hardened 18CrMo4 steel, Archives of Mechanical Technology and Automation 31(4), pp. 53–62, 2011.

26. *Linins, O., Krizbergs, J., Boiko, I.:* Surface texture metrology gives a better understanding of the surface in its functional state, Key Engineering Materials 527, pp. 167–172, 2013. **27.** *Kundrak J., Deszpoth I., Molnar V.:* Decision support method for the applicability of hard turning, Cutting and Tools in Technological System 96, pp. 110–120, 2022. **28.** *Zawada-Tomkiewicz, A.:* Analysis of surface roughness parameters achieved by hard turning with the use of PCBN tools, Estonian Journal of Engineering 17, art no 88, 2011. **29.** *Novak, M.:* Surface quality of hardened steels after grinding, Manufacturing Technology 11(1), pp. 55–59, 2011. **30.** *Kundrak, J., Molnar, V., Markopoulos, A.P.*: Joint machining: Hard turning and grinding, Cutting and Tools in Technological System 90, pp. 36–43, 2019. **31.** *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.

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ПОХИБКА ОКРУГЛОСТІ ТА ТОПОГРАФІЇ ЖОРСТКО ТОЧЕНИХ ПОВЕРХОНЬ

Анотація. *Точність і рельєф є важливими показниками прецизійно оброблених високоякісних поверхонь. Загартована сталь (16MnCr5) була проаналізована для отримання інформації про вплив технологічних даних і зв'язку між проаналізованою точністю (округлість) і параметрами шорсткості (S_a, S_z, S_{sk}, S_{ku}). Було виявлено, що швидкість подачі має значний вплив на параметри округлості та шорсткості, і існують сильні зв'язки між округлістю та цими значеннями параметрів шорсткості: коефіцієнти кореляції коливалися між 0,78 та 0,85. У цьому дослідженні тверді точені поверхні аналізуються з точки зору точності та якості поверхні на основі деяких широко застосовуваних параметрів кваліфікації. Вимірювання округлості та топографії були проведені та порівняні для отримання інформації про вплив параметрів різання. В експерименті використовувалася загартована сталь 16MnCr5, яка широко використовується в автомобільній промисловості. Для отримання точної інформації про якість поверхні було застосовано 3D аналіз топографії. Експеримент проводився на основі факторного плану експерименту та були розраховані основні статистичні показники для детального розуміння зв'язку між округлістю та проаналізованими параметрами шорсткості. На основі експерименту з механічної обробки (жорстке точіння) та вимірювань округлості та шорсткості (S_a, S_z, S_{sk}, S_{ku}) було проаналізовано вплив параметрів різання на виміряні параметри та порівняно зв'язок між даними шорсткості та округлості. Результати можна інтерпретувати для жорсткого точіння та в аналізованому діапазоні параметрів (a_p = 0,05–0,35 мм; v_c = 120–240 м/хв; f = 0,04–0,2 мм/об). Виміряні значення S_a та S_z, отримані при швидкості подачі 0,04 мм/об, нижчі, ніж отримані при 0,2 мм/об, що підтверджує висновки кількох попередніх досліджень. Похибка круглості жорстко точених поверхонь вища, якщо використовується більша величина подачі або глибина різання. Підвищена похибка виникає внаслідок овальності та/або крайніх викидів обробленої поверхні. Існують сильні зв'язки (високий коефіцієнт кореляції) між аналізованими значеннями шорсткості та округлості: r = 0,78–0,85. Обмеження дослідження полягає в тому, що обробку проводили лише за 8 комбінаціями параметрів. Більш точні результати можна отримати, застосовуючи більше (3 або 4) рівнів даних режимів різання.*

Ключові слова: *округлість; 3D рельєф поверхні; жорстке точіння; прецизійна обробка*