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A. Nagy, J. Kundrak, Miskolc, Hungary

CHANGES IN THE VALUES OF ROUGHNESS PARAMETERS ON FACE-MILLED STEEL SURFACE

Abstract. *In this paper, the roughness characteristics of the face milled surface were investigated made with a parallelogram insert ($\kappa_r = 90°$) on C45 steel. Changes in surface roughness were analyzed for the specific surface created by the milling movement conditions (rotational main movement and linear feed motion). The topography was created by a tool moving in the plane of symmetry of the workpiece, which produced double cutting-edge grooves. We found that the roughness varies in different parts of the resulting pattern, and we analyzed its nature and the magnitude of the variance based on the average over the entire surface. Also, in parallel measurements, the R_z parameter was at its maximum in the symmetry plane, and in the perpendicular direction roughness values are the lowest in the middle and increase with distance.*

Keywords: *face milling; surface roughness; distribution of roughness.*

1 INTRODUCTION

Face milling is a commonly used machining method worldwide, and because high quality flat surfaces can be produced with high productivity, machined parts are used for a wide range of applications. To expand this and incorporate components, many researchers are conducting research on surface roughness and machining surface topography to better meet operational requirements. Most of the analyses are characterized primarily by analyzing the impact of the cutting data, using different methods and under varying machining conditions.

Bhardwaj et al. [1] analyzed the surface roughness of EN353 steel alloy with a PVD carbide insert by Response Surface Methodology (RSM) method, with Box-Cox transformation. The influence of cutting speed v_c, feed rate f_z, depth of cut a_p, and nose radius r_ε were investigated. They found that increasing the feed increased the roughness, since greater forces affect the tool and the grooves are deeper as the distance between the milling tracks increases. However, increasing the cutting speed reduced the roughness because higher cutting temperatures occur, which softens the workpiece material. Increasing the peak radius also reduced roughness and had a negligible effect on the depth of cut.

Subramanian et al. [2] investigated face milling of Al7075-T6 aluminum workpiece for roughness development with the aim of selecting appropriate cutting data to achieve the desired roughness. In addition to the cutting data (v_c, f_z and a_p), the effects of r_ε and rake angle γ were also observed. The RSM method was used to determine the mean roughness R_a and was validated with experimental results.

A decrease in roughness was observed as the rake angle and nose radius were increased, and the roughness increased as the depth of cut increased. When increasing feed rate and cutting speed, roughness first decreased and then increased after a given value. The minimum roughness was achieved at $f_z = 0.03$ mm/rev and $v_c = 115$ m/min.

Seth et al. [3] analyzed the flatness and roughness of the milled surface of ASTM A216 cast steel, where the tool rotation n, the feed rate f_z and the depth of cut a_p were varied. They found that as the feed increased, the roughness increased as well, but decreased with cutting speed and first decreased then increased with depth of cut.

Benardos et al. [4] used Artificial Neural Networks (ANN) and Taguchi methods to study the effect of depth of cut, feed rate, cutting speed, and coolant lubricant and tool wear on roughness in aluminum milling. It was found that the feed had the greatest influence on the change in roughness, followed by feed force component, depth of cut, and coolant lubricant, in decreasing order.

Baek et al. [5] studied the effect of feed rate and insert runouts on roughness on a face-milled surface. They found that larger runouts led to higher maximum surface roughness R_t, and the mean (R_a) and maximum height roughness (R_t) both increased with the increase of the feed rate within the investigated range. A mathematical model was used to estimate the expected roughness and to use it to determine the optimum feed rate based on the given roughness value and material removal rate.

Filho et al. [6] performed milling experiments where the effect of changing cutting speed and feed rate on tool life and surface roughness were investigated. It has been observed that although both tool wear and surface roughness increased with time, the increase in roughness was not closely related to the increase in wear.

Gong et al. [7] investigated the fatigue wear development and pattern of a coated carbide tool insert in high speed face milling of SKD11 hardened steel, by analyzing the tool surface, cutting force, and surface roughness of the workpiece. Increasing the material removal rate was observed to increase the intensity of flank wear, cutting force, and surface roughness, with the same trend. Furthermore, it was concluded that during the initial wear phase, the value of roughness had a jump increase. Although the amount of flank wear was relatively low, the condition of the rake face continued to deteriorate due to repeated impact loading. The friction between the tool and the workpiece was unstable, resulting in a jumping change in the surface roughness. During the steady wear phase, the flank wear and cutting forces increased rapidly, leading to a rapid increase in surface roughness.

Earlier analyses were conducted by our institute. Felhő and Kundrák examined the 2D and 3D surface roughness parameters with a theoretical machined surface model. The effect of feed rate variation on C45 steel workpieces was investigated [8], taking into account axial runouts of the tool edges and changes in chip cross section. It was found that the accuracy of the estimation method increased with increasing feed rate and the runouts had a significant effect on roughness. In another work [9] the topographies of surfaces made with the same cutting data but with tools with different edge geometries were compared. It was found that while the model is generally useful for estimating 2D and 3D roughness, it is not suitable for all edge geometries. A case for this, for example, is cutting with tools with an edge parallel to the surface.

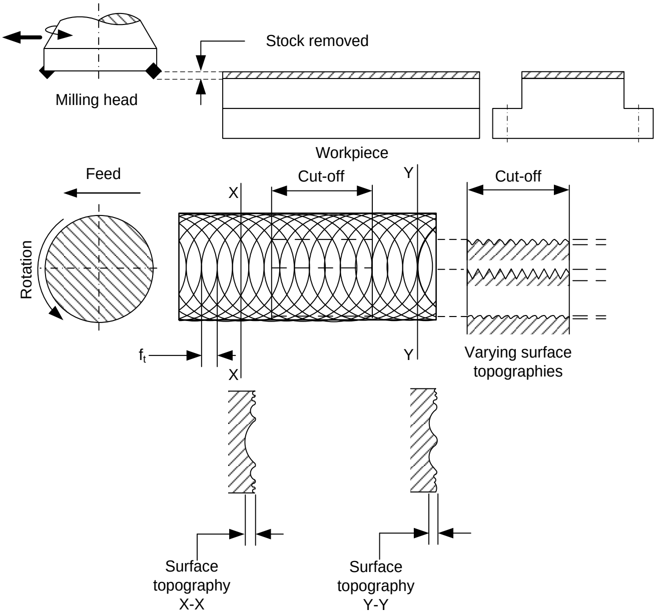


Figure 1 – Change in surface roughness with measurement direction in face milling [13]

Nagy and Kundrák investigated the influence of changing the feed [10] and cutting speed [11] on 2D and 3D surface roughness of specimens produced by cutting experiments. Overall, it was found that in the investigated ranges, the increase in feed and roughness (R_a, R_z and S_a, S_z) was almost linear, and increasing the cutting speed resulted in a decrease in roughness. In addition, maximum roughness was observed in the symmetry plane of the workpieces, and different values were measured in pairs on the entry and exit sides (from the tool's point of view).

When investigating the roughness of the face-milled surface, in most cases (supported by the examples above) the specimens are only measured parallel to the feed direction at a point where theoretically maximum values are obtained. However, there are little or no publications examining the roughness distribution of the entire machined surface (Figure 1). Other parts of the created surfaces are also connected to joining surfaces of the parts, which have other roughness values [12-14].

This is of particular importance for contacting surfaces, so in this article we examine how the characteristic imprint of the tool edge path at various points on the surface affects roughness. The mean value of the whole surface is taken as the base value and the deviation of the values measured at the test points is examined.

2 EXPERIMENTAL CONDITIONS

For roughness measurement, a PerfectJet MCV-M8 vertical CNC milling machine was used for experiments on a normalized C45 non-alloy carbon steel specimen with tensile strength 580 MPa and Brinell hardness 207 HBW [15]. The surface was milled by dry machining with a Sandvik R252.44-080027-15M milling head equipped with a single Sandvik R215.44-15T308M-WL coated parallelogram carbide insert ($\kappa_r = 90°$, $\gamma_o = 0°$, $\alpha_o = 11°$, $r_\varepsilon = 0.8$ mm). With the diameter of Dt = 80 mm, the tool cut the 58 mm wide specimen with a symmetrical setting, the workpiece length was 50 mm. In one turn, the cutting edge of the tool cut forward and scratched the surface backward, creating double cutting-edge grooves. The cutting speed used was $v_c = 300$ m/min, the depth of cut was $a_p = 0.8$ mm and the feed rate was $f_z = 0.3$ mm/rev. Photos of the tool and the workpiece and the milled surface are shown in Figure 2.

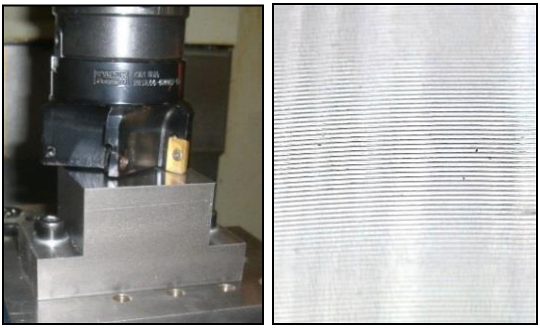


Figure 2 – The cutting system and the milled surface

The 2D roughness measurements were conducted on an AltiSurf 520 3D surface topography measuring device (Figure 3). The surface was measured with a CL2 confocal chromatic sensor which has a vertical resolution of 0.012 µm. The measurement results were evaluated with AltiMap Premium.

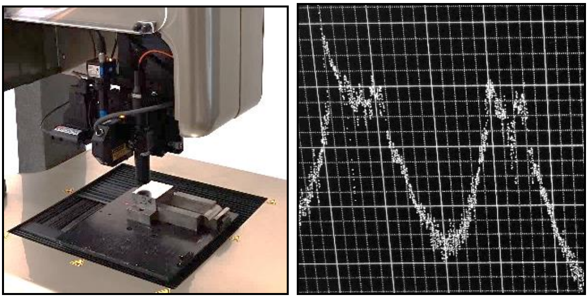
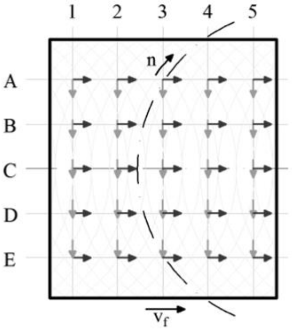


Figure 3 – The measurement system and the profile drawn

To measure the changes in roughness values, 5 measurement planes were taken at the same distance from each other, and 5 measurement locations were placed at the same distance along each plane. First, the measurement was made in planes parallel to the feed direction, one of these (plane **C**) is the symmetry plane of the workpiece, where the tool axis moves along the feed direction. Subsequently, it was measured in a direction perpendicular to the feed, during which the midpoints of the central measurements were aligned to the symmetry plane. Figure 4 explains the system used, along with the coordinate system. In all locations, the measurement length was 4 mm according to ISO 4287:1997 and the cut-off length was adjusted to 0.8 mm during evaluation.



Plane No.	↦ [mm]	Plane Letter	↓ [mm]
1	5	**A**	9
2	15	**B**	19
3	25	**C**	29
4	35	**D**	39
5	45	**E**	49

Figure 4 – Roughness measurement points on the face milled surface

3 RESULTS OF EXPERIMENTS

There are many parameters to describe the roughness of a surface. Of these, average surface roughness (R_a) is one of the most widely accepted and used in the industry. However, from a functional point of view (fitting, abrasion behavior, abrasion resistance, lubrication properties, etc.), we also consider several parameters important. Therefore, we report the parameters: mean roughness R_a, height of roughness profile R_z and relative load length ratio R_{mr}. The measurement results are summarized in Table 1. Gaussian filtering was used for all parameters. The load length expressing the fraction of the material was taken at a cut level (depth) of 1 µm, considering the arithmetic mean of the R_z values for all measurements (Fig. 5).

Table 1 – Measurement results in different measuring directions

		parallel to $\overrightarrow{v_f}$					perpendicular to $\overrightarrow{v_f}$				
		1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
R_a [µm]	**A**	1.528	1.552	1.557	1.520	1.552	0.760	1.150	0.986	0.993	1.175
	B	1.128	1.033	0.906	0.843	0.926	0.442	0.574	0.648	0.435	0.541
	C	1.759	1.821	1.892	1.757	1.515	0.206	0.158	0.161	0.159	0.145
	D	2.033	1.924	1.879	1.857	1.847	0.488	0.515	0.590	0.549	0.606
	E	1.553	1.565	1.572	1.598	1.605	1.258	1.222	1.198	1.292	1.221
R_z [µm]	**A**	6.892	6.929	6.963	6.562	6.876	4.260	5.651	4.944	5.054	5.860
	B	5.287	5.402	4.392	4.216	4.383	2.841	3.706	4.800	2.973	3.564
	C	8.785	8.396	8.295	8.208	8.144	1.394	0.959	1.122	1.296	1.053
	D	8.089	7.675	7.453	7.283	7.141	3.243	3.269	3.319	3.326	4.175
	E	6.880	6.842	6.805	6.945	6.933	6.082	5.882	5.960	6.182	5.670
R_{mr} [µm]	**A**	4.50%	5.27%	4.94%	7.94%	5.24%	7.65%	4.19%	4.47%	3.36%	5.19%
	B	6.72%	2.34%	7.09%	7.72%	9.56%	4.29%	5.37%	1.72%	3.22%	3.91%
	C	2.85%	2.93%	3.31%	2.31%	3.12%	66.8%	89.6%	94.4%	61.9%	97.6%
	D	5.68%	7.34%	8.34%	10.3%	8.43%	2.16%	2.62%	3.03%	3.41%	1.79%
	E	6.88%	6.98%	7.00%	7.78%	8.04%	7.12%	6.59%	7.00%	7.97%	4.25%

4 DISCUSSION

For the evaluation we need a base to which we compare the difference in the values measured at each point. As shown in Figure 1, depending on which point on the surface is being measured the values of the roughness parameters may be very different based on the edge impression; thus, we use the average of the measured values. Figure 5 shows the mean roughness of the measured values of the parameters (R_a, R_z, R_{mr}) determined from parallel and perpendicular measurements as well. In this figure, roughness values are also visually represented by map charts, with lighter sections indicating higher values.

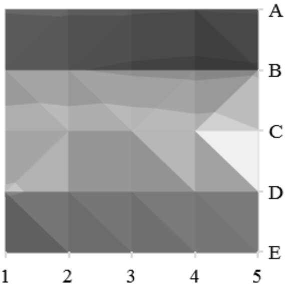
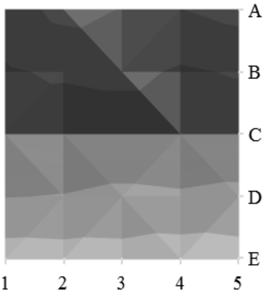
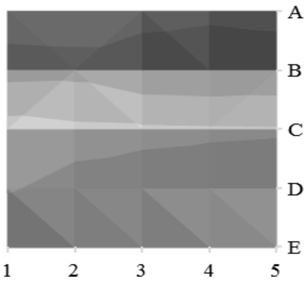
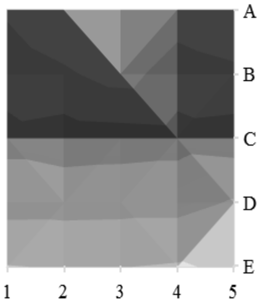
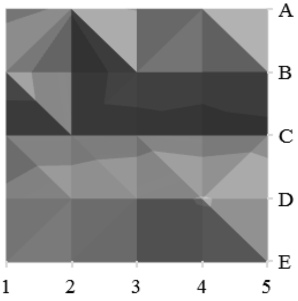
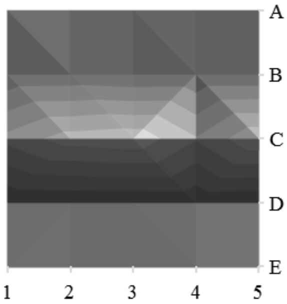
	$\bar{x}$	parallel to $\overrightarrow{v_f}$	perpendicular to $\overrightarrow{v_f}$
R_a [µm]	1.124		
R_z [µm]	5.367		
R_{mr} [µm]	13.04%		

Figure 5 – Arithmetic mean values and measurement results plotted

Figure 5 shows clearly that the surface roughness values are very diverse. This is a consequence of the theoretical profile created by the milling motion shown in Figure 1, and the fact that both directions of measurement were taken into account in determining the base values, and in addition the effects analyzed several times in our previous articles. Thus, for example, down-milling on one side of the symmetry plane and up-milling on the other side creates the topography. We chose this average value (as determined from bidirectional data) because every time two surfaces are allowed to move in any direction during operation or there may be a shift in one direction or another during assembly, it can be a good starting point for analyzing wear and/or tribological relationships. Of course, for the study of unidirectional displacements, we consider it useful to base the measurement points on the average of the values measured in that direction.

The percentage deviation of R_a and R_z values from the base value in the measurement directions at each point of the surface is determined (Table 2).

Table 2 – The magnitude of deviations from the base at each measurement location

		parallel to $\overrightarrow{v_f}$					perpendicular to $\overrightarrow{v_f}$				
	Δ	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
R_a [%]	**A**	34.04	36.14	36.58	33.33	36.14	-32.37	2.28	-12.30	-11.66	4.51
	B	-1.05	-9.39	-20.53	-26.05	-18.77	-60.69	-48.91	-42.36	-61.33	-51.90
	C	54.30	59.74	65.96	54.12	32.89	-81.66	-85.92	-85.67	-85.85	-87.06
	D	78.33	68.77	64.82	62.89	62.02	-56.58	-54.15	-47.55	-51.17	-46.07
	E	36.23	37.28	37.89	40.18	40.79	11.90	8.69	6.60	14.98	8.59
R_z [%]	**A**	24.29	24.96	25.57	18.34	24.00	-20.63	5.30	-7.88	-5.83	9.18
	B	-4.65	-2.58	-20.79	-23.97	-20.96	-47.07	-30.95	-10.57	-44.60	-33.60
	C	58.43	51.42	49.59	48.03	46.87	-74.03	-82.13	-79.10	-75.86	-80.38
	D	45.88	38.41	34.41	31.34	28.78	-39.57	-39.10	-38.16	-38.03	-22.21
	E	24.08	23.39	22.72	25.25	25.03	13.31	9.60	11.05	15.19	5.64

The percentage differences are also shown in graphs, where the values are grouped according to the parallel planes (Figure 6).

Analyzing the results, it can be concluded that roughness shows significant differences at different points of the surface. When looking at the values independently of the measurement directions, the minimal values of R_a=0.145 μm, R_z=0.959 μm, R_{mr}=1.72%, and the maximal R_a=2.033 μm, R_z=8.785μm, R_{mr}=97.6% (Table 1). If we take the values in parallel planes, the deviation is smaller. It can also be stated that the base (average) value is increased by the measurements parallel to the feed direction, while the base value is decreased by perpendicular measurements. Furthermore, the mean roughness (R_a) and the height of the roughness (R_z) diagrams in each direction of measurement show very similar characteristics.

In the measuring direction parallel to the feed motion, the maximum values were measured in two planes, the maximum of R_a in plane **D** and the maximum of R_z in symmetry plane **C**. At the values of the parameter R_z, it is clear that the greatest difference in height of the roughness profile can be measured in the symmetry plane, when examining the surface parallel to the feed direction. This is consistent with the fact that the grooves formed by the tool edge are at their greatest distance in this plane (Figure 1). R_a is less sensitive to this.

In planes equidistant from plane **C**, typically similar values were measured. The differences can be explained by the fact that the milling in the **E-C** planes is up-milling, while in the **C-A** planes down-milling occurs [10]. An exception to this regularity is the values measured in plane **B**. The reason for this requires further investigation.

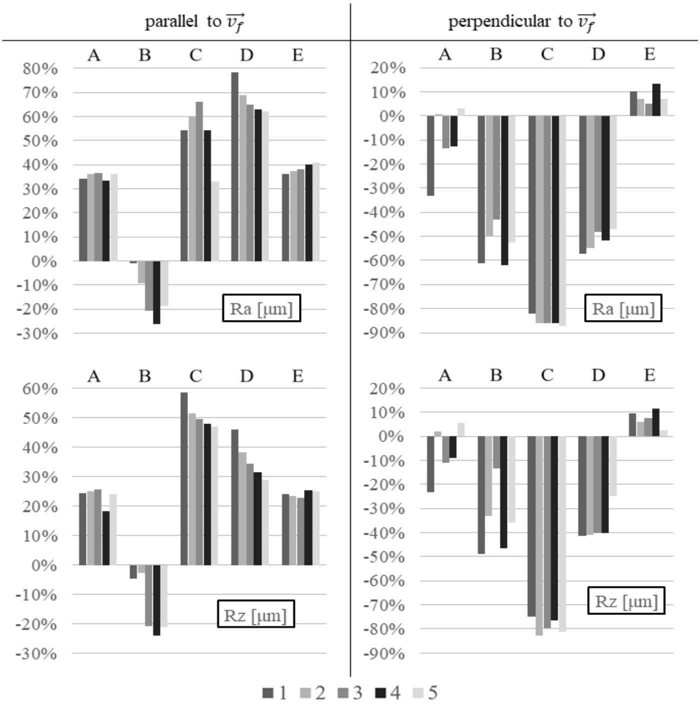


Figure 6 – Magnitude of deviations from the arithmetic mean in graphs

For measurements in the perpendicular direction, a relatively large deviation of the values along the planes is observed. Higher values are found farthest from the mid-plane, on both the entry and exit sides.

Between planes **1-5** there is a small variance of the values in the side (**A** and **E**) planes, and a larger deviation in the intermediate planes. However, in most cases, observing only the values of a chosen numbered plane do not change the characteristics of the graphs. In most cases, even larger deviations are observed in the perpendicular direction of measurement, but the latter statement is equally valid here.

5 CONCLUSIONS

This article presents a study of the roughness of a face milled flat surface with a carbide insert to a C45 steel specimen. During the research, surface roughness was measured at 5×5 locations parallel and perpendicular to the feed direction. The arithmetic mean of the roughness values of the measured points was taken as the base value as the characteristic roughness value. The values of the measurement points were also analyzed in relation to this base. The experiments confirmed that the values of the roughness parameters change on the face milled surface depending on the measurement direction and location. The experiments verified that the planes parallel to the feed show a difference depending on their position and distance based to the symmetry plane, which is primarily determined by the position of the cutting edge on the entry or exit side. On the basis of the examinations, the average of the roughness values measured at the measuring points was equally distributed on the surface. In addition, the roughness values measured in the plane of symmetry can be recommended for the evaluation of the milled surface roughness.

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References: **1.** *Bhardwaj, B., Kumar, R., Singh, P.K.:* An improved surface roughness prediction model using Box-Cox transformation with RSM in end milling of EN 353, Journal of Mechanical Science and Technology 28(12), pp.5149-5157. (2014). **2.** *Subramanian, M., Sakthivel, M., Sudhakaran, R.:* Modeling and analysis of surface roughness of AL7075-T6 in end milling process using response surface methodology, Arabian Journal for Science and Engineering 39(10), pp.7299-7313. (2014). **3.** *Sheth, S., George, P.M.:* Experimental investigation and prediction of flatness and surface roughness during face milling operation of WCB material, Procedia Technology 23, pp.344-351. (2016). **4.** *Benardos, P.G., Vosniakos, G.C.:* Prediction of surface roughness in CNC face milling using neural networks and Taguchi's design of experiments, Robotics and Computer-Integrated Manufacturing 18, pp.343-354. (2002). **5.** *Baek, D.K., Ko, T.J., im, H.S.:* Optimization of feedrate in a face milling operation using a surface roughness model, International Journal of Machine Tools and Manufacture 41, pp.451-462. (2001). **6.** *Filho, C.J., Diniz, A.E.:* Influence of cutting conditions on tool life, tool wear and surface finish in the face milling process, Journal of the Brazilian Society of Mechanical Sciences 24, pp.10-14. (2002). **7.** *Gong, F., Zhao, J., Jiang, Y., Tao, H., Li, Z., Zang, J.:* Fatigue failure of coated carbide tool and its influence on cutting performance in face milling SKD11 hardened steel, International Journal of Refractory Metals and Hard Materials 64, pp.27-34. (2017). **8.** *Felhő, C., Kundrák, J.:* Effects of setting errors (insert run-outs) on surface roughness in face milling when using circular inserts, Machines 6(2), 14. (2018). **9.** *Felhő, C., Nagy, A., Kundrák, J.:* Effect of Shape of Cutting Edge on Face Milled Surface Topography, Proceedings of the International Symposium for Production Research 2019, pp.525-534. Springer, Cham, 2019. **10.** *Nagy, A., Kundrak, J.:* Investigation of surface roughness characteristics of face milling, Rezanie I Instrumenty V Tekhnologicheskih Sistemah 90, pp. 63-72. (2019). **11.** *Nagy, A., Kundrak, J.:* Effect of cutting speed on surface roughness: face milling of steel with a parallelogram insert, MultiScience - XXXIII. microCAD International Multidisciplinary Scientific Conference, Miskolc-Egyetemváros, Magyarország, 2019., Paper: D1-4, pp. 1-10. **12.** *Smith GT.* Cutting Tool Technology: Industrial Handbook. London: Springer, 2008. **13.** *Felhő, C., Karpuschewski, B., Kundrák, J.:* Surface roughness modelling in face milling, PROCEDIA CIRP 31, pp. 136-141., (2015). **14.** *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). **15.** European Steel and Alloy Grades, C45, https://tinyurl.hu/GtDr/

Антал Надь, Янош Кундрак, Мішкольц, Угорщина

ЗМІНИ ЗНАЧЕНЬ ПАРАМЕТРІВ ШОРСТКОСТІ ПОВЕРХНІ СТАЛЕВИХ ЗАГОТОВОК ПІСЛЯ ТОРЦЕВОГО ФРЕЗЕРУВАННЯ

Анотація. *У цій статті представлено дослідження шорсткості обробленої торцевим фрезеруванням поверхні сталевої заготовки фрезою з твердосплавною пластиною. Для вимірювання змін в значеннях шорсткості були взяті 5 площин вимірювання на однаковій відстані одна від одної, і 5 точок вимірювання були розміщені на однаковій відстані уздовж кожної площини. Спочатку вимір робився в площинах, паралельних напрямку подачі, одна з яких - це площина симетрії заготовки, де вісь інструменту рухається вздовж напрямку подачі. Згодом зміни вимірювали в напрямку, перпендикулярному подачі, де середні точки центральних вимірювань були вирівняні по площині симетрії. Середнє арифметичне значення шорсткості виміряних точок було взято в якості базового характеристичного значення шорсткості. Значення точок вимірювання також були проаналізовані щодо цієї бази. Можна констатувати, що базове (середнє) значення шорсткості збільшується при вимірах, паралельних напрямку подачі, в той час як базове значення зменшується при перпендикулярних вимірах. Крім того, діаграми середньої шорсткості (Ra) і висоти шорсткості (Rz) в кожному напрямку вимірювання показують дуже схожі характеристики. Експерименти підтвердили, що значення параметрів шорсткості змінюються на поверхні фрезерованій поверхні в залежності від напрямку і розташування вимірювання. Експерименти підтвердили, що площини, паралельні подачі, показують різницю в залежності від їх положення і відстані від площини симетрії, яка в основному визначається положенням ріжучої кромки на стороні входу або виходу. На підставі досліджень середнє значення шорсткості, виміряне в точках вимірювання, було рівномірно розподілено по поверхні. Крім того, значення шорсткості, виміряні в площині симетрії, можуть бути рекомендовані для оцінки шорсткості фрезерованої поверхні.*

Ключові слова: *торцеве фрезерування; шорсткість поверхні; розподіл шорсткості.*