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ROUGHNESS INVESTIGATION OF SINGLE AND DOUBLE CUTTING MARKS ON FACE MILLED SURFACE

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Abstract. *In machining with defined cutting edge tools, in some rotational tool processes (e.g. face milling) the tool edge may scratch the surface of the workpiece one more time, depending on the cutting conditions, during one revolution of the tool. As a result, the topographies with single or double cutting marks will be different from each other. The deviation, depending on its size, can also affect the functional performance (e.g. friction conditions) of the operating surfaces. In this article, face-milled topographies created with a symmetrical setting and with single or double milling marks are compared according to the magnitude of the roughness and the degree and nature of the inhomogeneity.*
Keywords: *face milling; surface roughness; back-cutting of milling tool; secondary material removal.*

1. INTRODUCTION

The aim of manufacturing is to create products and their parts with the required accuracy and surface quality so that structural, functional and other usage requirements can be achieved. Such expectations can be wear or corrosion resistance, sealing ability with or without sealing material, thermal and electrical conduction, possibility of coating, aesthetics, etc. In many cases these can be achieved by machining, where the tool separates the material of the workpiece, thereby creating chips and a new machined surface. The shape of the tool edge(s) is imprinted on the surface, creating a pattern specific to each cutting process [1]. In addition, many – often unknown – factors take place during the process (tool wear, change in chip cross-section, change in cutting force, vibrations, workpiece material heterogeneity, etc.) [2]. These machining process characteristics and phenomena that influence the formation of topography were described for turning in an Ishikawa diagram by Bajic et al. [3]. We supplemented this with a few points, considering the specifics of machining with rotating tools, which are circled on the graph (Figure 1). Many researchers study the effects of these parameters on roughness and countless articles are published about the results of their analyses.

In the case of machining with defined cutting edge tools, it is usually characteristic that during finishing the final topography is formed by the tool, leaving a single impression of its edge(s) [4]. However, in machining with rotating tools (e.g. face milling), it happens that the tool edges cut the surface of the workpiece twice due to the movement conditions. In the beginning of the cutting, the edges separate material from the workpiece in each revolution [5], which is their front cutting movement. In this case, cycloid arcs are formed on the surface shifted by a feed distance. During the further feed movement, the same edges may scratch the already machined surface again during their return, during which further material separation, "re-cutting" occurs [6]. In this case double milling marks are formed on the surface [7]. In this case the texture consists of lozenge-like protrusions, and they become smaller as they move further away from the plane of symmetry – the path of the tool axis [6]. This occurs when the tool axis is perpendicular to the machined plane surface [6] and the length of the feed movement is greater than the radius of the tool.

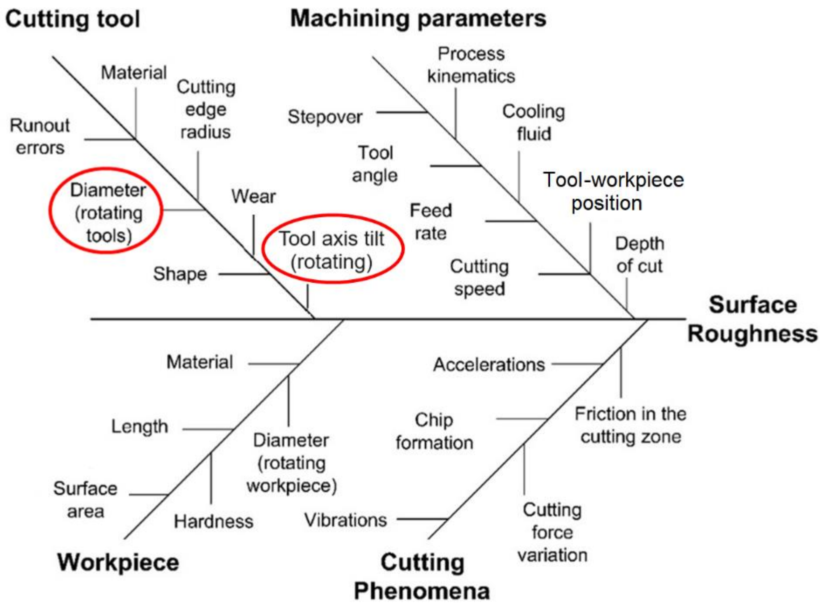

Figure 1 – Factors affecting surface roughness [3]

Milled surfaces having both single [8] and double [9] cutting marks are produced in industry for the same purpose of use, but these topographies have different characteristics. A lower roughness can be measured on the topography with double milling marks, where the degree of reduction is significantly affected by the phase difference (the ratio of the distance between a front-cutting and its nearest back-cutting mark measured in the symmetry plane and the feed), depending on the diameter of the tool and the magnitude of the feed [7,10]. The roughness is also affected by the fact that the front- and back-cutting traces are not of the same depth, because of the bending of the tool due to the cutting forces and the elastic recovery of the workpiece material after cutting [11]. As the difference in depth decreases, the values of Ra and Rt decrease slightly [10].

No matter the texture, the face milled surface topography is various and its roughness is different when measured in various places, which was investigated on experimental surfaces [12,13] and on theoretical topographies produced analytically [14]. One of the main findings is that the profiles measured in the direction parallel to the tool advance are regularly repeated (periodic) with the feed distance. The roughness values are maximal in the symmetry plane, they decrease in other parallel planes the further away from it [12,15], and the degree of difference increases with increasing feed [16]. In perpendicular direction, the number of peaks increases on measured profiles further away from the symmetry plane, and their Ra and Rz values decrease.

In addition to the technological data and machining process characteristics, the roughness of the face milled surface topography is also influenced by the type of the texture; however, the topographical and functional effect of the secondary material separation is not known in sufficient depth. In this article, the aim of the study is to compare the topographic characteristics of the two types of patterns and to determine how the surface roughness and its deviations change due to the secondary material separation.

2. EXPERIMENTAL CONDITIONS

Milling experiments were carried out on a PerfectJet MCV-M8 vertical milling center. The workpiece material was C45 unalloyed carbon steel in a normalized state, on which the plane surfaces were machined on an area of 58×50 mm^2. They were cut with a Dijet SEKN 1203 AFTN type, JC5030 quality insert mounted on a Canela 0748.90.063 milling head, whose nominal diameter was D_t = 63 mm, the cutting edge angles were $\kappa_r = 45°$; $\gamma_o = 0°$; $\alpha_o = 20°$, and the width of the chamfer was 0.85 × 45° (Figure 2). We set the feed f_z = 0.4 mm/rev, the depth of cut a_p = 0.8 mm and the cutting speed v_c = 300 m/min. The tool axis was in a perpendicular position to the machined surfaces, so the range of the feed movement of the workpiece determined the formed impression. As the workpiece was moved until the tool axis line generated only front-cutting traces (Figure 2a), creating the M1 surface. However, the other workpiece was moved under the tool with a full length feed, where due to the motion conditions the edges scratched the surface twice (during front-cutting and back-cutting movement as well), producing surface M2 (Figure 2b). During the examination, we take into account that according to the directions of the cutting and feed speeds, two sides of the surfaces separated by a symmetry plane can be distinguished; up-milling takes place on the workpiece from the start of cutting until the symmetry plane; after that, down-milling occurs. When evaluating the deviations and distributions of roughness values, the surface parts are marked with a superscript, where *U* is up-milled, *D* is down-milled.

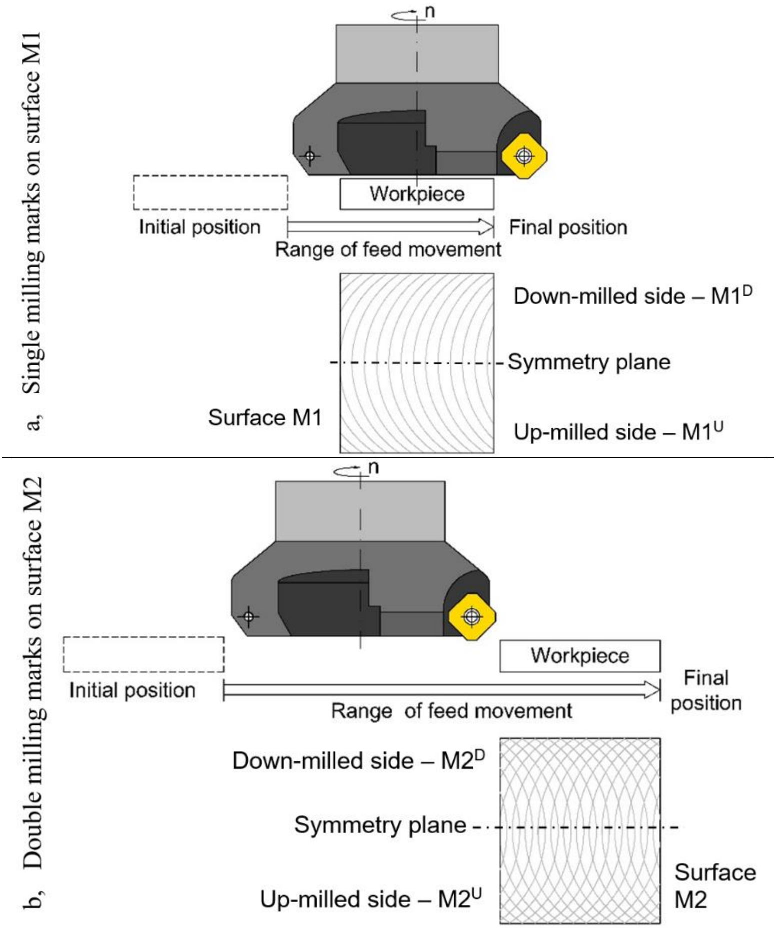

Figure 2 – Range of workpiece feed movement for creating topography having single (a) or double cutting marks (b)

This was followed by topography measurement on an AltiSurf 520 3*D* surface measuring device with a CL2 confocal chromatic sensor. To evaluate the roughness deviations, 25 measurement points on the surface were determined in such a way that they designate examination planes parallel and perpendicular to the feed (Figure 3). These are important for milling regarding the kinematics and the position of the points. One of the planes in the feed direction is identical to the symmetry plane (path of the tool axis) (plane C), and the other parallel planes are taken at 10 mm distance between each other (planes A, B, D, E). The planes perpendicular to these (planes I–V) have a distance of 8 mm between each other. At the measurement points, profiles were measured in directions parallel and perpendicular to feed, and they were evaluated at 4 mm length with a section length of 0.8 mm.

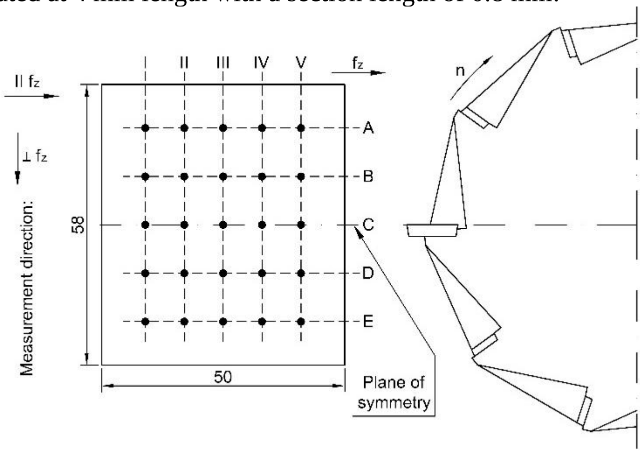

Figure 3 –Position of measurement points and planes on surfaces

Table 1 – R_a and R_z parameter values of profiles measured in feed direction

	Single cutting marks – Surface M1							**Double cutting marks – Surface M2**					
	I	**II**	**III**	**IV**	**V**	*ΔR*		**I**	**II**	**III**	**IV**	**V**	*ΔR*
Ra [µm]	2.48	2.53	2.51	2.50	2.51	*0.05*	**A**	1.64	1.48	1.52	1.52	2.09	*0.61*
	3.05	3.03	3.03	3.02	3.05	*0.03*	**B**	1.12	1.11	1.16	1.26	1.49	*0.38*
	3.20	3.19	3.21	3.21	3.17	*0.04*	**C**	2.82	2.93	2.99	2.91	2.87	*0.17*
	3.05	3.08	3.06	3.09	3.08	*0.04*	**D**	2.11	2.33	2.55	2.56	2.64	*0.53*
	2.57	2.58	2.60	2.60	2.65	*0.08*	**E**	2.25	2.46	2.40	2.37	2.43	*0.21*
ΔR	*0.72*	*0.66*	*0.70*	*0.71*	*0.66*			*1.70*	*1.82*	*1.83*	*1.65*	*1.38*	

Rz [µm]	10.52	10.24	10.25	10.25	10.58	*0.34*	**A**	8.49	8.49	7.61	7.18	8.82	*1.64*
	12.69	12.65	12.58	12.61	12.71	*0.13*	**B**	6.16	6.11	6.59	7.27	8.67	*2.56*
	13.07	13.04	13.21	13.24	13.20	*0.20*	**C**	10.70	11.33	11.44	11.15	11.12	*0.74*
	12.76	12.80	12.73	12.87	12.96	*0.23*	**D**	7.94	8.64	9.30	9.50	9.65	*1.71*
	10.90	10.88	10.86	10.99	11.14	*0.28*	**E**	8.77	9.63	9.22	9.49	10.88	*2.11*
ΔR	*2.55*	*2.80*	*2.96*	*2.99*	*2.62*			*4.54*	*5.22*	*4.85*	*3.97*	*2.45*	

3. RESULTS

We report the values of the average R_a and maximum R_z height of roughness profiles, which are the most frequently evaluated in industry, measured in the direction parallel to the feed (Table 1) and perpendicular to it (Table 2). In the tables, the degree of the deviations (*ΔR*) in each examination plane is given in italics.

Table 2 – R_a and R_z parameter values of profiles measured in the direction perpendicular to feed

	Single cutting marks – Surface M1							**Double cutting marks – Surface M2**					
	I	**II**	**III**	**IV**	**V**	*ΔR*		**I**	**II**	**III**	**IV**	**V**	*ΔR*
Ra [µm]	1.40	1.49	1.51	1.47	1.46	*0.11*	**A**	0.97	0.94	0.97	1.06	1.34	*0.40*
	0.57	0.62	0.63	0.63	0.63	*0.06*	**B**	0.54	0.55	0.56	0.53	0.51	*0.05*
	0.27	0.19	0.19	0.20	0.19	*0.08*	**C**	0.17	0.19	0.20	0.18	0.19	*0.03*
	0.64	0.63	0.63	0.63	0.62	*0.02*	**D**	0.49	0.52	0.51	0.59	0.58	*0.10*
	1.55	1.57	1.53	1.56	1.59	*0.06*	**E**	1.59	1.59	1.54	1.65	1.56	*0.11*
ΔR	*1.28*	*1.38*	*1.34*	*1.36*	*1.40*			*1.42*	*1.40*	*1.34*	*1.47*	*1.37*	
Rz [µm]	7.45	8.12	7.64	7.35	7.59	*0.77*	**A**	6.03	4.80	5.72	5.55	7.46	*2.66*
	4.01	4.12	3.80	3.71	3.79	*0.41*	**B**	3.43	3.35	3.47	3.19	3.07	*0.40*
	1.49	1.08	1.11	1.25	1.02	*0.47*	**C**	1.15	1.21	1.31	1.26	1.62	*0.47*
	3.92	3.74	3.80	4.03	3.75	*0.29*	**D**	3.22	3.07	2.65	3.28	3.44	*0.79*
	7.92	8.52	8.01	7.92	7.94	*0.60*	**E**	7.40	7.09	6.74	8.17	7.28	*1.43*
ΔR	*6.43*	*7.44*	*6.90*	*6.67*	*6.92*			*6.25*	*5.88*	*5.43*	*6.91*	*5.84*	

4. DISCUSSION

After completing the roughness measurements, we examined and compared the topographies made with the two types of textures, based on the data presented in Tables 1–2. During this, we analyzed the distribution and deviations of the measured roughness values in the examination planes on the surface according to the direction of measurement. On the topographies, the distribution is illustrated in Figures 4 and 6 with surface diagrams. The magnitude of the values and their deviations in the planes taken parallel (A–E) and perpendicular (I–V) to the feed are shown in Figures 5 and 7 with bar diagrams, where the height of the columns indicates the degree of the deviation.

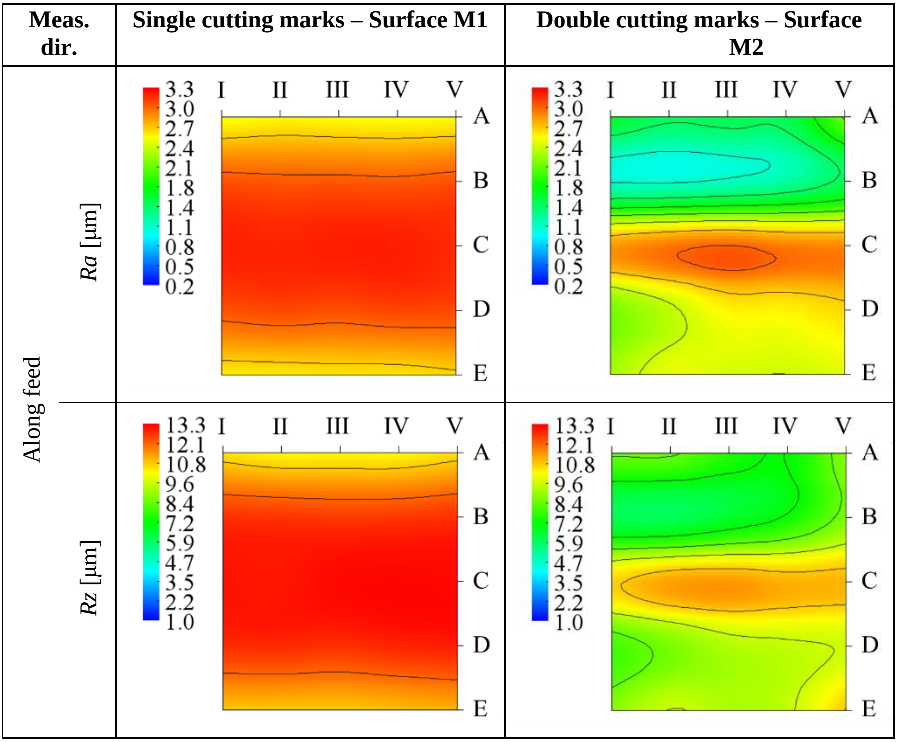

Figure 4 – Distribution of roughness values in the direction of the feed on the examined topographies

First, we analyze the R_a and R_z values of the profiles measured in the feed direction. On the surface with single milling marks (M1), the values in planes A–E parallel to the feed show negligible differences, which can be considered as the standard deviation of the measurement results (Figure 5). The values are maximal in the symmetry plane C and they decrease in both directions further away from it (Figure 5). In the planes perpendicular to the feed (I–V), the deviations of the values are similarly between 21–25% (Table 1). Also, the distribution of values in these planes is the same (Figure 4). Negligible differences between the measured values can be seen on the $M1^U$ and $M1^D$ sides of the surface, at the same distance from the symmetry plane (Figure 5). Among the parameters, the values of R_z show greater variety compared to R_a (Figure 4).

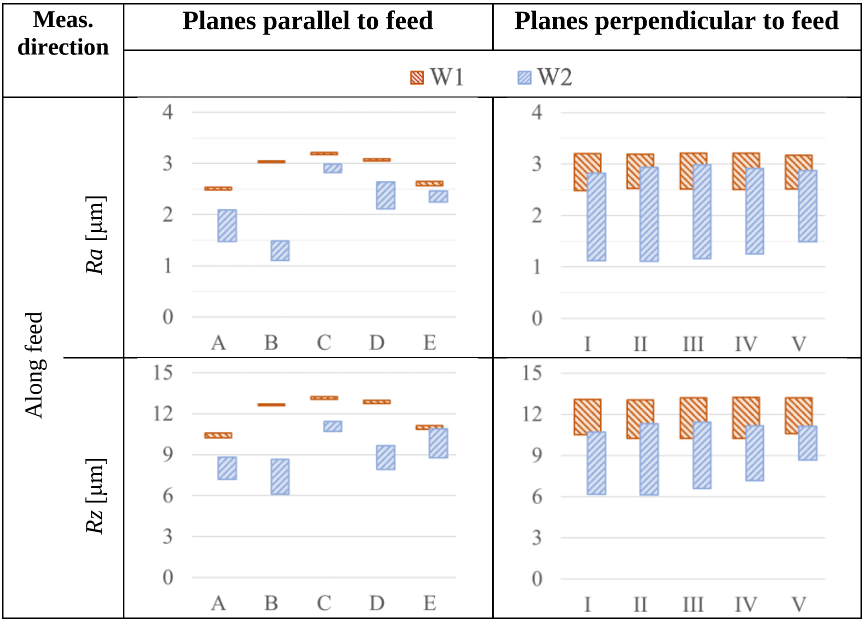

Figure 5 – Roughness values measured in feed direction and their deviations in the examination planes

As a result of the secondary material separation, the values of the investigated parameters in the planes parallel to the feed direction (A–E) decreased by 4–64% for Ra and 2–52% for R_z in the measurement points (Table 1). They are also maximal in plane C, and they decrease in both directions towards the edges of the investigated area (Figure 4). But as they are scarcely smaller in the middle plane than the values measured here on the M1 surface (by 9% on average for R_a, by 15.2% on average for R_z), then the further away from it the degree of decrease is significant; max. 64% for R_a, max. 52% for R_z (Figure 5). On this topography, we already see remarkable deviations between the values of the two sides of the surface separated by the symmetry plane (Figure 5); the values on the down-milled ($M2^D$) side are higher than those on the $M2^U$ surface part. This observation is identical to the finding described in [18]. The largest deviation can be seen in plane A, on the up-milled side ($M1^U$, Fig. 5), where the degree of difference was also maximal (on the surface) and almost the same in our previous investigation [19]. In the numbered I–V planes, the deviation of the values is significantly larger compared to the differences calculated on the M1 surface, its extent is 1.5–2.5 times (Table 1). The distribution of values has also changed; further away from plane C in both directions, the values of points decrease but not in all cases (Figure 4). Ra parameter values showed more sensitivity to the variations in roughness on this surface. In summary, the roughness difference on the topography created with double milling marks is large and is significantly higher compared to the surface with a single impression (2.7 times in R_a and 1.87 times in R_z).

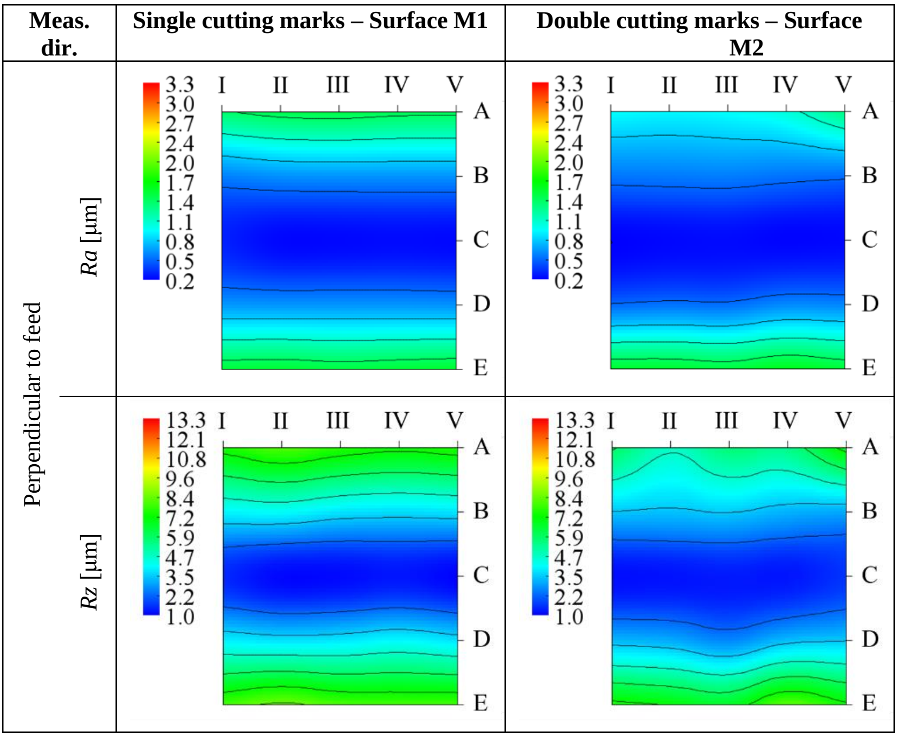

Figure 6 – Distribution of roughness values measured in the direction perpendicular to the feed on the examined topographies

Next, we evaluate the results of profiles measured in the direction perpendicular to the feed, starting with the M1 surface. The roughness values in the feed direction planes A–E are almost identical (Figure 7), the differences in them are ΔR_a = 0.02–0.11 µm, ΔR_z = 0.29–0.77 µm (Table 2). This contributes to the fact that the distance between adjacent measurement points taken in the feed direction is an integer multiple of the feed value, so profiles measured on the same plane that is parallel to the feed direction, are theoretically identical. The values of the R_a and R_z parameters examined on the topography are the lowest in the C symmetry plane and increase in two directions moving further away from it (Figure 7), similar to findings in [17]. The values and their distribution of the surface sides $M1^U$ and $M1^D$ are symmetrically almost identical to the symmetry plane (Figure 6). In the numbered (I–V) planes, as shown in Figure 7, the degree of deviations of the R_a values is almost the same (1.28-1.4 µm), in the case of the R_z parameter they are very similar (6.43–7.44 µm), the distributions are the same (Figure 6).

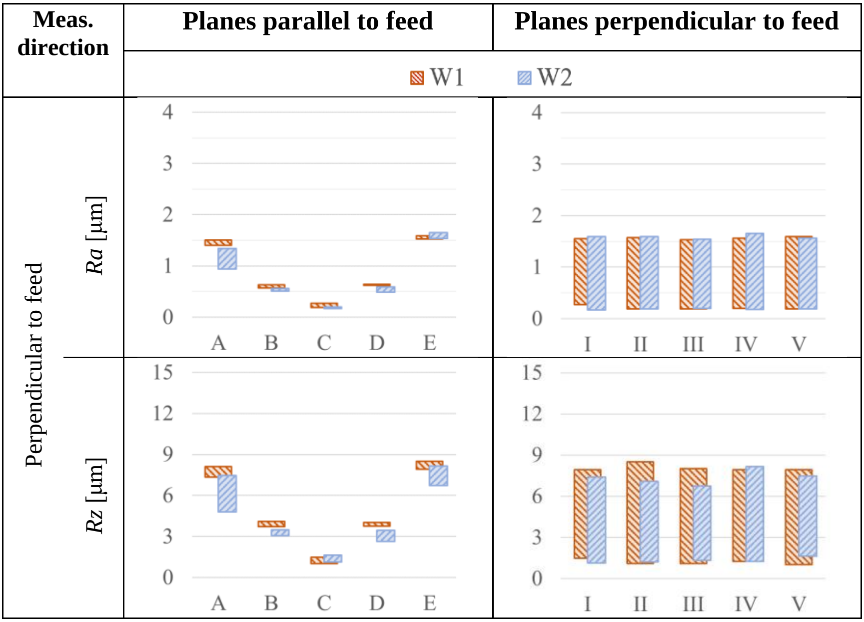

Figure 7 – Values measured in the direction perpendicular to the feed and their deviations in the examination planes

On the M2 topography with double milling marks, the values of points in planes B, C and D are minimally lower and the degree of deviations is similar compared to the same points on the M1 surface (Figure 7). On the other hand, in the extreme planes A and E, a greater degree of depreciation and larger deviations are characteristic, based on the comparison with the M1 surface (Figure 7). In the numbered (I–V) planes, the magnitude of deviations is slightly smaller compared to the M1 surface (Figure 7). However, the distribution of values has changed to the extent that higher values can be found on the $M2^U$ up-milled surface side (Figure 6), similar to the measurement results in the feed direction. The roughness deviations of the profiles measured in this direction are shown by the values of the R_z parameter with greater sensitivity than the values of R_a (Figure 7). Based on the measurement results (Table 2), we conclude that the roughness deviations of profiles measured in this direction are small.

5. CONCLUSIONS

In this article, the topography and roughness of plane surfaces face-milled with a symmetrical tool setting were examined, considering the effect of secondary material separation (back-cutting movement of the tool edge). The results can be summarized as follows.

- Based on the results of profile measurements in the feed direction, the values of R_a and R_z parameters on surfaces M1 and M2 are maximum in the symmetry plane and they decrease in both directions the further away from it (except that they increase in the extreme plane A). On the surface where secondary material separation occurred, the values decrease (minimally in the plane of symmetry, significantly towards the edges of the surface), while their deviations are larger.
- The results of the profile measurements in the direction perpendicular to the feed show that the values on the M1 and M2 surfaces are minimal in the symmetry plane and increase in two directions further away from it. In the case of secondary material separation, the decrease in roughness is small in most points, and the degree of deviations on the surface is greater. We find that by measuring the profiles in this direction, the change in roughness is less than when measured in the feed direction.
- The distribution of R_a and R_z values on the two – differently – machined surfaces differs regardless of the direction of measurement. While on the M1 topography with single cutting marks, the value decrease is almost the same on the up-milled ($M1^U$) and down-milled ($M1^D$) side of the surface further away from the symmetry plane, while on the surface with double milling marks (M2), the roughness values are higher on the up-milled side ($M2^U$).

- Different degrees of deviations can be measured on the face milled surfaces in the two measurement directions, so the tribological (e.g. friction) conditions may change if the milled surface in contact moves along these directions.
- During face milling, the secondary material separation changes the roughness values measured in different parts of the topography and their deviations. Under the investigated experimental conditions, the unevenness of the surface is best expressed by the R_z values measured in the feed direction.

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ДОСЛІДЖЕННЯ ШОРСТКОСТІ ОДИНАРНИХ І ПОДВІЙНИХ СЛІДІВ РІЗАННЯ НА ТОРЦЬОВО ФРЕЗЕРОВАНІЙ ПОВЕРХНІ

Анотація. *При обробці за допомогою інструментів з певною різальною крайкою, в деяких процесах при використанні обертального інструменту (наприклад, торцьове фрезерування) крайка інструменту може ще раз протягом одного оберту інструменту, подряпати поверхню заготовки, залежно від умов різання. В результаті топографії з одинарними або подвійними відмітками різання будуть відрізнятися одна від одної. Відхилення, залежно від його розміру, також може вплинути на функціональні характеристики (наприклад, умови тертя) робочих поверхонь. У цій статті торцево-фрезеровані топографії, створені з симетричною установкою і з одинарними або подвійними фрезерними мітками, порівнюються відповідно до величини шорсткості, ступеня і характеру неоднорідності. За результатами вимірювань профілю в напрямку подачі значення параметрів* R_a *і* R_z *на поверхнях максимальні в площині симетрії і зменшуються в обидві сторони, чим далі від неї (за винятком того, що збільшуються в крайній площині). На поверхні, де відбулося відокремлення вторинного матеріалу, величини шорсткості зменшуються (мінімально в площині симетрії, ближче до країв поверхні), при цьому їх відхилення більші. Розподіл значень* R_a *і* R_z *на двох – по-різному – оброблюваних поверхнях відрізняється незалежно від напрямку вимірювання. У той час як на топографії M1 з одинарними мітками різання зменшення значення майже однакове на фрезерованій (M1U) і фрезерованій (M1D) стороні поверхні, більш віддаленій від площини симетрії, тоді як на поверхні з подвійними фрезерними мітками (M2) значення шорсткості вищі на фрезерованій стороні (M2U). На торцевих фрезерованих поверхнях можна вимірювати різні ступені відхилень у двох напрямках вимірювання, тому трибологічні (наприклад, тертя) умови можуть змінитися, якщо фрезерована поверхня, що контактує, рухається в цих напрямках. Під час торцевого фрезерування вторинне розділення матеріалу змінює значення шорсткості, виміряні на різних ділянках рельєфу, та їх відхилення. У досліджуваних експериментальних умовах нерівність поверхні найкраще виражається значеннями* R_z, *виміряними в напрямку подачі.*

Ключові слова: *торцеве фрезерування; шорсткість поверхні; зворотне різання фрезерного інструменту; видалення вторинного матеріалу.*