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EFFECT OF CHANGING THE MILLING HEAD DIAMETER ON THE INHOMOGENEITY OF THE MACHINED SURFACE TOPOGRAPHY

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Abstract. *The geometry of the tool and the workpiece plays a decisive role in the formation of the topography of a machined surface. Depending on the kinematic conditions of the machining process, they influence both the magnitude of surface roughness and the irregularity of the topography. This paper presents an investigation of the variation in topographical inhomogeneity resulting from changes in the tool diameter used in face milling. The results showed that increasing the diameter – while keeping all other parameters constant – significantly increased the values of amplitude and functional roughness parameters measured on the surface at the same measurement position. The decreasing trend of the values with increasing distance from the path of the tool axis was consistent, and its magnitude gradually diminished at measurement locations taken at greater distances. However, when the distance was expressed as a proportion of the tool diameter, the values exhibited similar degrees of variation.*
Keywords: *face milling; surface roughness; distribution of roughness; tool diameter.*

1. Introduction

The components of mechanical engineering products are manufactured with the required accuracy and surface quality so that they can meet the specified structural, functional, and other performance requirements throughout their intended service life [1]. One of the most common ways to achieve this is through machining. During the process, the tool penetrates the material of the workpiece and, while removing chips, generates new surface(s) [2]. The cutting edge(s) leave an imprint on the surface, the characteristics of which are fundamentally determined by the relative motions of the tool and the workpiece, the tool edge geometry, and the feed rate [3].

Face milling is most commonly applied for producing planar surfaces due to its high productivity and the good dimensional accuracy and surface quality achievable on the machined surface (e.g., IT8 dimensional accuracy [4] and R_a = 0.8 μm surface roughness [5]). For this reason, many researchers investigate the influence of machining parameters on surface quality. In the following, the influence of several factors on the surface roughness are presented.

The influence of cutting parameters (e.g., cutting speed, feed, depth of cut) on surface roughness has been widely investigated [6]. The roughness can be decreased with decreasing feed values. In most cases, it has the highest influence on the surface roughness, followed by the cutting speed and the depth of cut [7]. However, it was reported in a study where aluminum workpieces were milled, that the feed rate had less significant effect than the the axial depth of cut [8]. A decrease of 50% in R_a parameter value was achieved with the increase of the cutting speed but only to a certain extent; in the study [8] the further increase of the spindle speed from 4000 rpm – i.e., the increase of the cutting speed – deteriorated the roughness. The nose radius of the tool is an important factor in the reduce of roughness; an increase in the radius from 0.4 mm to 1.2 mm caused a 62% decrease in the R_a value measured on the machined Ti-alloy [9]. Tool edge angles also affect the resultant roughness values on the machined surface; the roughness can be significantly decreased with an increase in the helix angle – thus a decrease in the shock load and vibrations – and minimally with the decrease of the radial rake angle [8,10]. Moreover, other characteristics of the milling tool, e.g., tool edge preparation, rounding [11], and run-out [12] also have an impact on the surface roughness [6]. However, another geometric attribute of the milling cutter – namely its diameter – may also influence the measured surface roughness values, an aspect that has been little studied so far.

In industry, larger-diameter milling tools are commonly used, as they allow for higher material removal rates, shorter machining times, and more efficient machine utilization [13]. However, an increase in surface roughness can also be expected, as observed in steel workpieces [14], influenced by factors exerting opposing effects. Although larger-diameter tools provide greater stiffness, the increased cutting forces, deflections, vibrations, and thermal loads associated with them may adversely affect the characteristics of the surface topography [15].

Due to the tool–workpiece kinematic relationships in face milling, the roughness characteristics can vary significantly across different regions of the surface, resulting in an inhomogeneous topography [16,17]. This may influence the functional properties of the surface (and their variability). The origin of such variations in roughness lies in the changes in the geometry of the cutting marks (their height, width, shape, etc.) on profiles measured at different locations and in different directions on the surface, as illustrated in Figure 1.

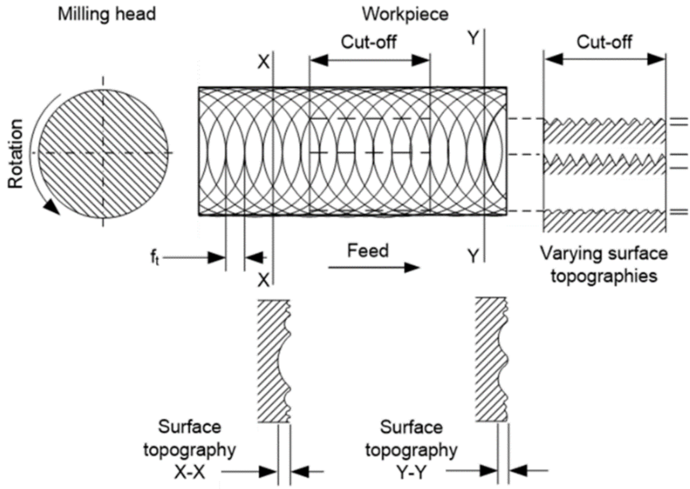


Figure 1 – Change in surface roughness with measurement direction in face milling [18]

The aim of the investigation is to experimentally determine how increasing the diameter of the milling tool affects the surface roughness and topographical inhomogeneity of a face-milled surface under identical cutting conditions.

2. Experimental conditions

For the investigation, machining experiments were carried out on a PerfectJet MCV-M8 vertical milling center. Three types of tools from Tungaloy's T2845 PM milling head series were used (050.05Z4, 063.05Z5W, and 100.05Z8). These tools share the same insert seat design and use the same mounted insert (OFEX 05T3AE, KH100 grade, $\kappa_r = 43°$, $\gamma_o = 25°$, $\alpha_o = 7°$, $r_\varepsilon = 0.4$ mm), but differ in their nominal diameters: $D_{t1} = 50$ mm (M50), $D_{t2} = 63$ mm (M63), and $D_{t3} = 100$ mm (M100). On three C45 steel workpieces, surfaces measuring 50 mm in length and 100 mm in width were prepared and machined under dry conditions. The set width of cut was equal to the tool diameter ($a_e = D_t$); 50 mm for the surface machined with the M50 tool, 63 mm for the one machined with the M63 tool, and 100 mm for the surface produced with the M100 tool. The additional cutting parameters were: $v_c = 300$ m/min, $a_p = 0{,}4$ mm, $f_z = 0.4$ mm/rev. The tool axis was positioned in the symmetry plane of the surfaces to be machined, perpendicular to them. During machining, the workpiece feed motion under the milling head continued from the start of cutting until the centers of the tool and the surface coincided, after which the tool was retracted from the cut. In this way, single milling marks were produced on the surfaces; however, unmachined areas remained within the width of cut, and double-cut surface regions were also formed during the back-cutting motion of the tool edge (Figure 2).

Roughness measurements on the machined surfaces were carried out using a CL2 confocal chromatic probe on an AltiSurf 520 three-dimensional surface topography measuring device. For examining roughness variations on the surfaces, several measurement points (marked with Roman numbers) were selected such that each of 5 defined measurement planes parallel to the feed direction, labeled **U**, **S** , and **D** (Fig. 2).

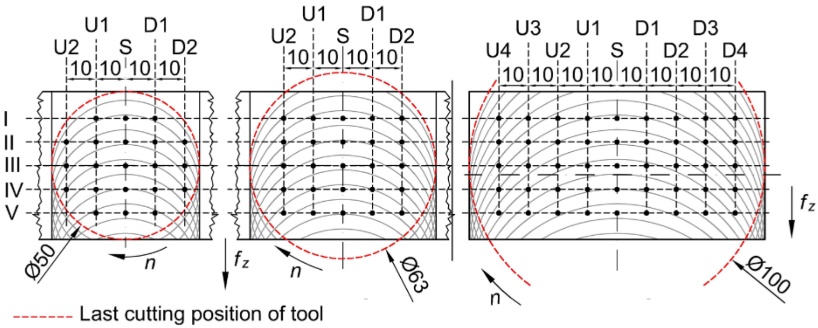


Figure 2 – Surfaces machined with tools of different diameters, along with the selected measurement planes and locations

The central plane corresponds to the path of the tool axis, which coincides with the symmetry plane of the surface. The others are positioned parallel to it, offset by 10 mm from one another on the up-milled (U planes) and down-milled (D planes) sides. Their number was determined according to the width of the milled surface (Figure 2). In the figure, the points indicate the centers of the measured profiles. The measurements were evaluated using AltiMap Premium v6.2 software. During measurement and evaluation, the requirements of the ISO 4287 standard were applied and followed. At each measurement location, profile measurements were taken in the feed direction with an evaluation length of 4 mm and a section length of 0.8 mm. No measurements were taken at positions that did not fall on the single cut region (i.e., those lying in unmachined or twice-machined areas, as shown in Figure 2).

3. Results and discussion

After measuring surface roughness at the designated measurement locations on the investigated surfaces (Figure 2), the roughness parameter values were evaluated. First, the roughness profiles measured at an identical location (**S-IV**) on each surface are shown in Figure 3. Second, the values of the most commonly used and examined

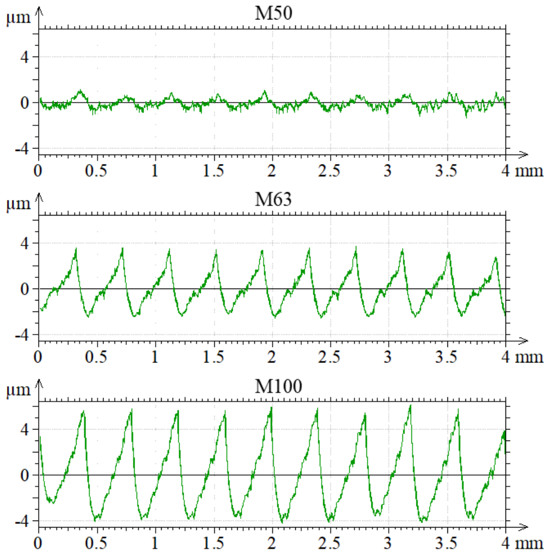


Figure 3 – Roughness profile curves recorded at position **S-IV** on surfaces machined with tools of different diameters

roughness indicators – R_a (arithmetical mean roughness) and R_z (maximum height of the profile) – are presented and analyzed. In addition, based on our previous investigations, the values of the R_p (maximum profile peak height) and R_k (reduced core roughness depth) parameters – which express topographical inhomogeneity with the highest degree – are also provided and studied. These values are organized by measurement planes, locations, and parameter type in Tables 1–2. The tables also include the range of values measured within the planes and on the surface, the latter expressed as a ratio relative to the arithmetic mean of the values measured on the topography. The distribution of roughness values on each surface is illustrated using contour map diagrams in Figure 4. Due to the large differences observed when changing the tool diameter, the diagrams present values expressed as ratios relative to the mean, indicated with an overline above the index.

Table 1 – Measured R_a and R_z values and their variations on the studied surfaces

	R_a [µm]							R_z [µm]					
Mille d	**I**	**II**	**III**	**IV**	**V**	**Range**	**Plane**	**I**	**II**	**III**	**IV**	**V**	**Range**
		0.12	0.11	0.11		0.01	**D2**		0.48	0.49	0.51		0.03
	0.22	0.21	0.22	0.23	0.25	0.04	**D1**	1.04	0.99	1.05	1.08	1.02	0.09

	0.27	0.26	0.26	0.30	0.27	0.04	**S**	1.33	1.18	1.23	1.48	1.35	0.30
	0.22	0.22	0.21	0.22	0.21	0.01	**U1**	1.20	1.12	1.06	1.07	1.04	0.16
		0.10	0.12	0.11		0.02	**U2**		0.47	0.56	0.51		0.09
						101%	**Surface**						104%
Milled with M63	**I**	**II**	**III**	**IV**	**V**	**Range**	**Plane**	**I**	**II**	**III**	**IV**	**V**	**Range**
	0.83	0.88	0.89	0.91	0.89	0.08	**D2**	3.71	3.95	3.94	3.87	3.89	0.24
	1.12	1.11	1.11	1.11	1.12	0.01	**D1**	5.23	5.22	5.24	5.03	5.25	0.22
	1.24	1.25	1.25	1.22	1.22	0.03	**S**	5.86	5.98	5.97	5.83	5.82	0.16
	1.12	1.11	1.11	1.11	1.14	0.03	**U1**	5.37	5.42	5.13	5.23	5.20	0.29
	0.86	0.87	0.89	0.88	0.83	0.06	**U2**	3.86	3.89	3.81	3.81	3.81	0.08
						40%	**Surface**						47%
Milled with M100	**I**	**II**	**III**	**IV**	**V**	**Range**	**Plane**	**I**	**II**	**III**	**IV**	**V**	**Range**
	1.17	1.15	1.19	1.17	1.20	0.05	**D4**	4.76	4.63	4.75	4.98	4.81	0.35
	1.83	1.77	1.78	1.75	1.82	0.08	**D3**	7.12	6.85	7.06	6.77	7.12	0.35
	2.19	2.20	2.20	2.20	2.20	0.01	**D2**	8.51	8.75	8.78	8.63	8.70	0.27
	2.42	2.45	2.41	2.47	2.36	0.11	**D1**	9.61	9.82	9.60	9.76	9.29	0.53
	2.45	2.44	2.41	2.41	2.41	0.04	**S**	9.64	9.59	9.43	9.43	9.37	0.27
	2.44	2.45	2.42	2.41	2.40	0.05	**U1**	9.46	9.44	9.59	9.39	9.45	0.20
	2.22	2.20	2.22	2.22	2.18	0.04	**U2**	8.88	8.81	8.93	8.83	8.98	0.17
	1.83	1.85	1.81	1.79	1.79	0.06	**U3**	7.38	7.27	7.18	7.15	7.18	0.23
	1.20	1.20	1.22	1.18	1.21	0.04	**U4**	5.03	5.03	5.02	4.82	4.96	0.21
						67%	**Surface**						67%

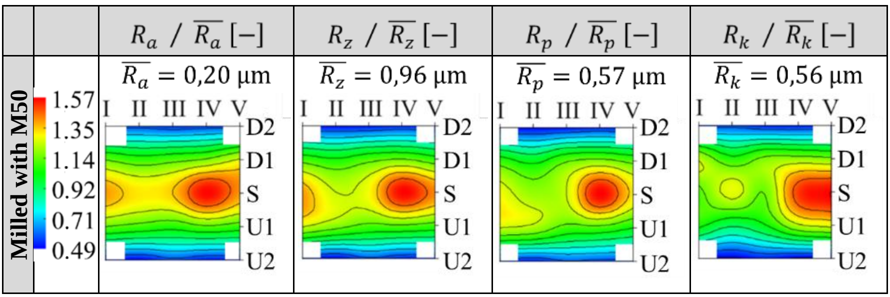
First, the effect of tool diameter on surface roughness is presented. The measured roughness values increased significantly with increasing diameter. This is easily compared in the symmetry plane (**S**), where the theoretical topographies of the investigated surfaces show identical cutting mark characteristics due to the same tool–workpiece motions, tool edge position, and feed value. At the measurement locations in this plane, increasing the diameter from Ø50 mm to Ø63 mm resulted in a 3.8–5.1-fold increase in amplitude parameters and a 4.5–6.2-fold increase in R_k. Further increasing the tool size to Ø100 mm led to an additional 1.6–2-fold increase, nearly the same extent for the analyzed parameters. This effect is likely due to the improved rotational stability associated with the larger diameter, resulting in more regular shape of the tool marks and more favorable shearing of the workpiece material. At the same time, for the smallest-diameter milling tool, the noisy and poorly defined tool marks observed on the topography indicate that the smaller rotating mass – and consequently the weaker gyroscopic stabilizing effect – amplifies vibrations in the machine–tool–workpiece system (Figure 3). The mechanism of this effect requires further investigation.

Table 2 – Measured R_p and R_k values and their variations on the studied surfaces

	R_p [µm]							R_k [µm]					
№:	**I**	**II**	**III**	**IV**	**V**	**Range**	**Plane**	**I**	**II**	**III**	**IV**	**V**	**Range**

		0.28	0.29	0.30		0.02	**D2**		0.32	0.29	0.28		0.04
	0.62	0.58	0.65	0.67	0.64	0.09	**D1**	0.69	0.59	0.65	0.66	0.65	0.10
	0.74	0.69	0.72	0.90	0.76	0.21	**S**	0.62	0.72	0.64	0.84	0.88	0.26
	0.72	0.70	0.63	0.63	0.59	0.13	**U1**	0.59	0.53	0.57	0.69	0.72	0.19
		0.30	0.34	0.33		0.04	**U2**		0.26	0.29	0.26		0.03
						108%	**Surface**						110%
Milled with M63	**I**	**II**	**III**	**IV**	**V**	**Range**	**Plane**	**I**	**II**	**III**	**IV**	**V**	**Range**
	2.01	2.18	2.07	2.10	2.10	0.17	**D2**	2.72	2.90	2.96	3.25	3.06	0.53
	2.97	2.94	2.91	2.85	2.93	0.12	**D1**	3.70	3.76	3.67	3.76	3.85	0.18
	3.43	3.53	3.52	3.45	3.46	0.10	**S**	3.86	3.99	3.95	3.76	3.85	0.23
	3.03	3.14	2.81	2.97	2.81	0.33	**U1**	3.55	3.61	3.70	3.62	3.92	0.37
	2.05	2.02	1.97	1.97	1.99	0.08	**U2**	2.80	2.67	2.91	2.86	2.52	0.39
						58%	**Surface**						43%
Milled with M100	**I**	**II**	**III**	**IV**	**V**	**Range**	**Plane**	**I**	**II**	**III**	**IV**	**V**	**Range**
	2.84	2.72	2.83	3.04	2.79	0.32	**D4**	3.00	2.98	2.84	2.96	3.09	0.25
	4.15	4.09	4.22	3.96	4.21	0.26	**D3**	5.12	4.64	4.65	4.69	4.97	0.48
	5.04	5.35	5.31	5.19	5.27	0.31	**D2**	5.66	5.65	5.83	5.71	5.49	0.34
	5.73	6.00	5.76	5.89	5.59	0.41	**D1**	6.67	6.24	6.43	6.46	5.96	0.71
	5.78	5.74	5.64	5.61	5.64	0.17	**S**	6.68	6.59	6.29	6.25	6.18	0.50
	5.76	5.72	5.89	5.70	5.71	0.19	**U1**	5.99	5.74	5.90	6.24	6.22	0.50
	5.51	5.41	5.53	5.40	5.58	0.18	**U2**	5.62	5.63	5.42	5.60	5.72	0.30
	4.58	4.46	4.50	4.38	4.47	0.20	**U3**	4.67	4.64	4.32	4.77	4.59	0.45
	3.09	3.09	3.15	2.95	3.01	0.20	**U4**	2.93	3.02	2.96	2.89	3.08	0.19
						70%	**Surface**						76%

Next, the variations in roughness values measured in the workpieces' symmetry plane (Figure 2, **S** plane) are analyzed. On the surfaces machined with the M63 and M100 tools, the values are nearly identical, differing by only 2–8%. In contrast, on the surface machined with the M50 tool, the differences are more pronounced: 15–28% for amplitude parameters and up to 35% for the functional parameter, due to the previously mentioned differences in rotational stability and vibrations (Tables 1–2). Within this plane, the values change randomly.



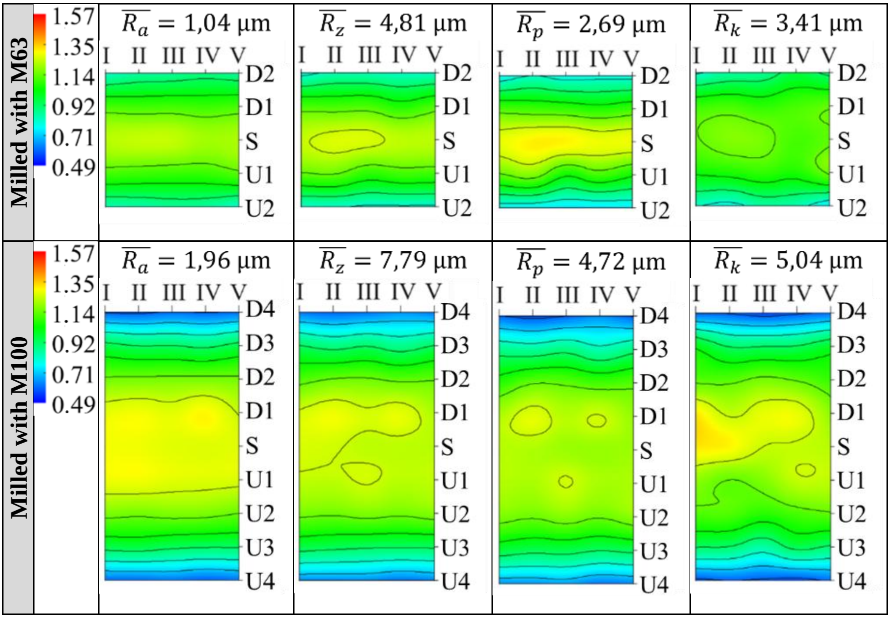


Figure 4 – Distribution of measured values on the investigated surfaces

In the following section, the variations in roughness values measured in the **U** and **D** planes – parallel to the **S** symmetry plane on the workpieces (Figure 2) – are analyzed. It can be observed that increasing the tool diameter reduced the differences in these planes for the investigated parameters (Tables 1–2). While the deviations on the surface machined with the M50 tool were mostly significant (5–28% for amplitude parameters, 11–35% for R_k), they were minor on the surface milled with the larger M63 tool (1–11% for R_a, R_z, and R_p; below 18% for R_k), and generally negligible on the surface cut with the M100 tool (ranging from 0.5–11%). The values within the planes – regardless of tool diameter – varies randomly. No trend was observed in the changes between the deviations determined in adjacent planes.

Next, the deviations and relative distributions of roughness values measured at the selected locations on the workpieces are evaluated as a function of tool diameter. The maximum differences in values determined on the investigated areas of the surfaces – the inhomogeneity of the topographies – were considerable but decreased with increasing tool diameter. On the surface machined with the M50 tool, deviations of 101–110% were reduced to 67–76% when the diameter was increased to Ø100 mm. Among the roughness parameters studied, the largest differences were observed for the R_k values.

Considering the distribution of roughness values on the topographies, it is identical that, for all tool diameters, the maximum values occur in the symmetry plane (Figure 4). The locations of the minimum values typically varied among the outer measurement planes farthest from the **S** plane, with negligible differences. On the surfaces, the values decreased with distance from the symmetry plane, by nearly the same degree on both the up- and the down-milled surface regions. Thus, the change in cutting movement direction has a negligible effect on the differences in values measured within the planes.

The changes in surface roughness values were further analyzed from two perspectives. For this purpose, the arithmetic mean of the measured values in the measurement planes was illustrated in Figure 5. First, considering a uniform-width area on the topographies (a 40 mm wide band between the **U2** and **D2** planes), increasing the tool diameter gradually reduced the deviations measured on the surface; machining with the M50 tool caused 101–110% variation, which was

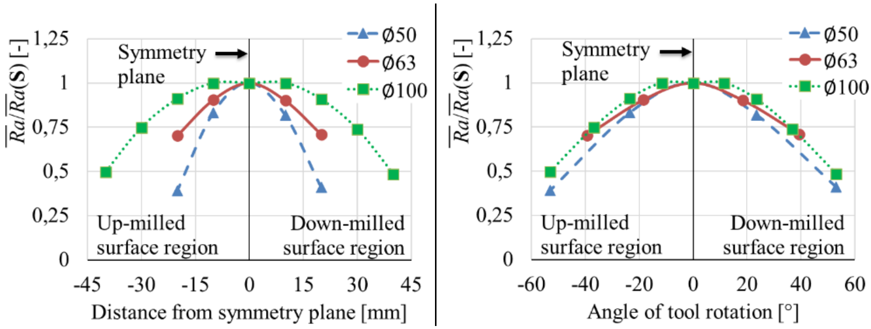


Figure 5 – Ratio of the mean of R_a values measured in planes to the mean value in the symmetry plane on surfaces milled with cutters of different diameters as a function of the distance from the symmetry plane (a) and the rotation angle of the tool marks from it (b)

decreased to 4–19% when using the Ø100 mm diameter milling cutter. At the same time, in adjacent planes shifted by the same distance, the measured values decreased less with increasing tool diameter (i.e., in Figure 5a, the curves corresponding to larger diameters are less steep). This behavior can be explained as follows: for two selected measurement planes of identical width, on a surface machined with a larger-diameter tool, the span angle of the tool marks becomes smaller (Figure 2), so their height and radial width – the values of roughness parameters – differ less. On the other hand, when the ratio of the tool diameter to the distance of a parallel measurement plane from the symmetry plane remains constant (where the intersection angles of the tool marks are the same), the values are typically similar, differing by less than 20% (Figure 5b).

4. Conclusions

In this study, the effect of the cutter diameter on the roughness of face-milled surfaces, topographical inhomogeneity were investigated with the amplitude R_a, R_z, R_p and the functional R_k parameters. Three cutters of different nominal diameters (Ø50 mm, Ø63 mm, Ø100 mm), each equipped with the same type of insert, were analyzed. The main findings are summarized below.

- It was found that increasing the cutter diameter led to a significant increase in roughness values at identical measurement positions. Increasing the diameter from Ø50 mm to Ø63 mm resulted in a 3.8–6.2-fold increase in roughness in the workpiece symmetry plane, while a further increase to Ø100 mm caused an additional 1.6–2-fold increase.
- With increasing milling head diameter, the differences in roughness values measured in planes parallel to the feed direction decreased. While the range on the surface machined with the smallest tool was 15–28% for amplitude parameters and 11–35% for the functional parameter, the use of larger cutters reduced these differences to a similarly small extent, 1–11%.
- The range of values measured on the examined surfaces – the topographical inhomogeneity – decreased from 101–110% to 67–76% as the cutter diameter increased from Ø50 mm to Ø100 mm.
- It was observed that at points located at equal distances from the workpiece symmetry plane (in any direction), roughness values decreased progressively less with increasing milling tool diameter. For a distance of 20 mm, differences gradually reduced from 6–38% to 1–14%. However, when the distance from the symmetry plane was expressed relative to the cutter diameter, roughness values changed to a similar extent compared to the central plane, with a maximum difference of 20%.
- Among the analyzed roughness parameters, the functional R_k values exhibited the largest changes with increasing tool diameter.

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Антал Надь, Мішкольц, Угорщина

ВПЛИВ ЗМІНИ ДІАМЕТРА ФРЕЗЕРНОЇ ГОЛОВКИ НА НЕОДНОРІДНІСТЬ ОБРОБЛЕНОЇ ПОВЕРХНІ

Анотація. *Геометрія інструменту та заготовки відіграє вирішальну роль у формуванні топографії обробленої поверхні. Залежно від кінематичних умов процесу обробки, вони впливають як на величину шорсткості поверхні, так і на нерівність топографії. У цій статті розглядається дослідження варіації неоднорідності топографії, що виникають через зміни діаметра інструмента, що використовується для фрезерування. Результати показали, що збільшення діаметра — при збереженні всіх інших параметрів незмінними — значно підвищує значення параметрів амплітуди та функціональної шорсткості, виміряних на поверхні в тій самій позиції вимірювання. Тенденція до зменшення значень із збільшенням відстані від траєкторії осі інструменту була стабільною, а її величина поступово зменшувалася на місцях вимірювання, зроблених на більших відстанях. Однак, коли відстань виражалася як пропорція діаметра інструмента, значення мали схожі ступені варіацій. Було встановлено, що збільшення діаметра фрези призводило до значного збільшення значень шорсткості в однакових положеннях вимірювання. Збільшення діаметра з Ø50 мм до Ø63 мм призвело до збільшення шорсткості площини симетрії заготовки у 3,8–6,2 рази, а подальше збільшення до Ø100 мм — додаткове збільшення у 1,6–2 рази. Зі збільшенням діаметра фрезерної головки різниця в значеннях шорсткості, виміряних у площинах, паралельних напрямку подачі, зменшувалася. Хоча діапазон поверхні, обробленої найменшим інструментом, становив 15–28% для параметрів амплітуди і 11–35% для функціонального параметра, використання більших різців зменшувало ці відмінності до подібно невеликої міри — 1–11%. Діапазон значень, виміряних на досліджуваних поверхнях — топографічна неоднорідність — зменшився з 101–110% до 67–76% у міру збільшення діаметра фрези з Ø50 мм до Ø100 мм. Було помічено, що в точках, розташованих на однакових відстанях від площини симетрії заготовки (у будь-якому напрямку), значення шорсткості поступово зменшувалися зі збільшенням діаметра фрезерного інструмента. На відстані 20 мм різниця* *поступово зменшувалася з 6–38% до 1–14%. Однак, коли відстань від площини симетрії виражалася відносно діаметра різального інструменту, значення шорсткості змінювалися порівняно з центральною площиною, з максимальною різницею 20%. Серед проаналізованих параметрів шорсткості функціональні значення R_k показали найбільші зміни при збільшенні діаметра інструмента.*

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