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INVESTIGATION OF FACE MILLED SURFACE TOPOGRAPHY ON C45 WORKPIECE ASSUMING MOVEMENT AT 30° AND 60° TO FEED DIRECTION

Abstract. *When surfaces with anisotropic texture are moved in different directions related to their assembled counterpart during operation, the friction conditions change, as they are determined by the lay of the topographies. In the article, contributing to the exploration of this characteristic, we analyze the inhomogeneity of the topography on a face milled plane surface with a symmetrical setting in sections at an angle of 30° or 60° to the feed direction. Roughness profiles are recorded at 13 points located equidistantly from each other in each measurement plane, and the degree and distribution of the roughness deviations are determined on the surface.*
Keywords: *face milling; surface roughness; distribution of roughness; direction-dependent characterization of topography*

1. Introduction

The aim of machining is to product parts of the required shape, dimensions, condition, etc., while achieving their prescribed accuracy. These are important factors, so that machines can fulfill their specified functions during the planned lifetime. Such expectations can be fatigue life [1], wear [2] and corrosion resistance, lubrication [3] and sealing ability, etc. [4]. To guarantee these, the specifications on the part drawings (tolerances, surface quality, condition) must be followed during production. One of the most common methods of production is cutting. During the process, the tool penetrates the material of the workpiece and creates a new machined surface while removing chips [5]. The surface is formed by impressions left on it by the edge(s) of the tool, which can be characterized as periodic or random.

A periodic topography is typically created with machining methods using a tool having defined edge(s), which form regularly repeated grooves. This has been investigated in different processes, mainly characterized by the values of profile roughness parameters. When examining the effect of tool coating and cutting data (cutting speed v_c, feed f, depth of cut a_p) on roughness and tool wear in the hard turning of corrosion-resistant steel, it was found that the maximum profile height R_z was significantly reduced, the friction and flank and crater wear rates were notably decreased, and the service life was increased with PVD coating [6]. The roughness value further decreased for increasing v_c and decreasing f and a_p. When turning hard-to-cut austempered ductile iron, the reduction of average roughness R_a value was achieved by increasing values of v_c and a_p in the studied ranges [7]. In rotational turning, the theoretical roughness profile in the reference plane was determined, and it was stated that half to one-sixth of values of R_a and R_z can be achieved with this process compared to roughness values measured on a surface peripheral turned with a traditional CNMG insert [8]. In drilling of a titanium alloy the value of R_a was also significantly affected by v_c, f and the helix angle [9]. There was a large increase in roughness due to the high rotation speed, thus the appearance of diffusion wear, as well as thermal softening and the increase in forming resistance. On burnished cylindrical surfaces, up to a third of R_a, R_q and R_z values were measured compared to the previous, turned topography if set to the appropriate values of burnishing force, feed and number of passes [10].

In addition to traditional profile roughness analysis, the 3*D* topographic parameters are increasingly used during the examination of surfaces machined with a defined edge tool due to their higher accuracy [11]. The topography of a hard turned hole in a hardened steel gear is anisotropic (the level of isotropy was below 5%), and by increasing the feed from 0.2 mm/rev to 0.3 mm/rev the wear resistance (based on values of S_p, S_{pk}, V_{mp} parameters) and the lubricant retention capacity (determined by Ssk and Svi indices) of the surface deteriorated [12]. In the comparative study of this process and grinding, where the relationships between the cutting parameters, the tribological characteristics of the surfaces, and the topographical parameters were analyzed, a significant correlation was found between S_p and V_{mp} indicating the wear resistance, between S_v and V_{vv} indicating the ability to keep the lubricant [3], and between V_{mp}, V_{vv} and S_{sk} parameters [13] that characterize both functions. In the case of burnishing after turning, it was further found that better wear resistance of the surfaces can be achieved based on the values of S_{sk} and S_{ku} parameters [14]. Topographies created by the methods discussed so far have the same feature that their roughness can be properly specified when measured in the feed direction (perpendicular to the cutting marks), and in this case the theoretical roughness profile is the same at any location on the surface.

The topography created with a rotating tool – milling – is one of the most commonly used process in industry, due to the productivity of its multi-point tool. Thus, face milling (where the tool axis is perpendicular to the machined plane surface) is also a frequently investigated research topic. The conditions that create a favorable topography of machined surfaces are often analyzed. Compared to machining methods discussed above, processes working with a rotated tool are characterized by the fact that the texture is more complicated, with the profile height of the topography changing in different parts of the surface. This can also be observed on the theoretical topography, which is determined only by the kinematic conditions, the tool edge geometry and the feed in the reference plane [15]. The nature of the texture is further complicated by the fact that the tool edges can scratch the already cut surface when turning back during their rotating movement. As a result of all this, there are large differences between profiles measured in several parallel planes in the feed direction and measured in different directions (Figure 1) [16]. This variability is supported by research results so far.

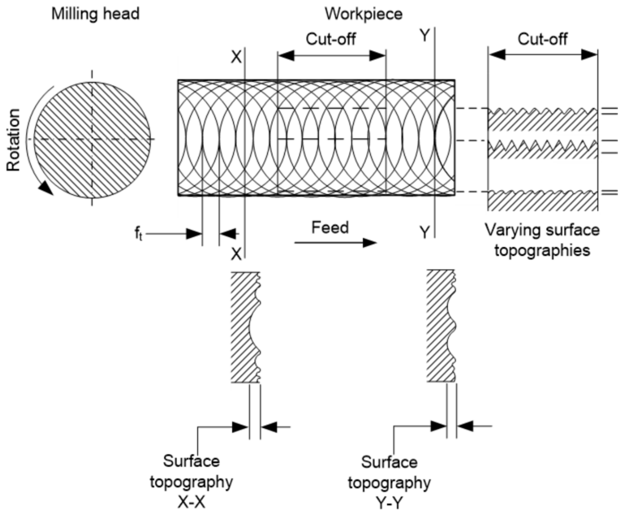


Figure 1 – Change in surface roughness with measurement direction in face milling [15]

During the examination of a developed face milled topography model, its great variability was pointed out, with profiles taken in different directions and locations [17]. An investigation of the depth of cut effect on roughness measured 5 surface elements on the finished face milled topography, one in the symmetry plane and the others in places mirrored to it [18]. The roughness of the surface parts were compared for the up-milled and down-milled part and the symmetry plane determined by the tool and workpiece movement conditions. Other researchers also considered the kinematic conditions, i.e. the different topographical parts formed by the path of the tool edge on the milled surface, for the analysis of which measurements were made at 5×5 locations [19]. It was found that the maximum roughness values can be measured in the plane of symmetry, and the values decrease in other parallel planes further away from it. The heights of the roughness profile curves in each plane changed accordingly. Furthermore, while on the theoretical topography the amplitude parameter values are the same on both sides of the symmetry plane at the same distance from it, on the real surface, larger values were observed on the side where the tool edge enters the workpiece. Theoretical and real roughness of surfaces face milled with increasing feed was investigated in three parallel measurement planes (in the symmetry plane and on both sides at equal distances from it) [20]. It was found that, the model showed good agreement with the real results; furthermore, the researchers pointed out the differences in roughness values in different parts of the topography, which are significant at larger feeds.

In summary, we conclude that the degree and characteristics of change in roughness on face milled surface have not been comprehensively analyzed, although they can significantly influence the functional properties of fitted surfaces. Therefore, the aim of the research described in the article is to contribute to the exploration of face milled topography characteristics; in this case specifying the degree and nature of the roughness deviations measured in different directions than the feed vector. For this, we assume that the milled surface of a part moves in relation to a connecting surface during operation, in the given direction(s) according to its function, where the characteristics of the surface texture in this direction are decisive. The presented study is a continuation of our previous analysis [21], where profiles measured in parallel and perpendicular directions to the feed were performed at different locations on the surface.

2. Experimental conditions

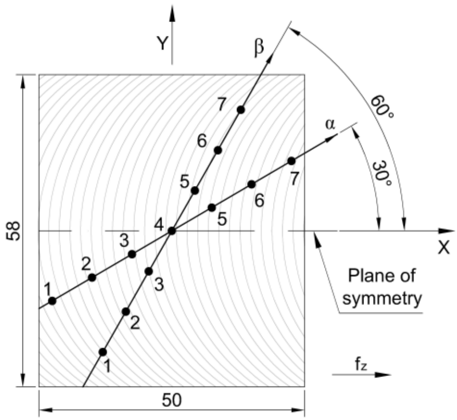
For the investigation we carried out an experiment. Conditions are summarized in Table 1.

Table 1 – Experimental conditions

Machining	
Machine tool	PerfectJet MCV-M8 vertical milling center
Workpiece material	normalized C45 unalloyed steel
Machined surface geometry	58 mm width, 50 mm length
Cutting tool	ATORN 10612120 (D_t = 80 mm, κ_r=43°)
Cutting insert	one ATORN OCKX 0606-AD-TR, HC4640 (γ_o=25°; α_o=7°; r_ε=0.5 mm)
Cooling-lubrication	No
Cutting strategy	Symmetrical tool-workpiece setting, only front-cutting traces on the surface
Cutting data	v_c=300 m/min, f_z=0.4 mm/rev/tooth, a_p=0.4 mm
Roughness measurement	
Measuring equipment	AltiSurf 520 3*D* topography measuring instrument
Measuring sensor	CL2 confocal chromatic probe
Evaluation length	4 mm
Section (cut-off) length	0.8 mm
Evaluation software	AltiMap Premium

First, we milled the plane surface in its full width, where the tool axis moved in its symmetry plane. The edge only formed front-cutting marks on the surface by setting the tool axis perpendicular to the surface during machining, and the workpiece was feed moved from the edge of the tool to the center.

This was followed by the roughness measurement. During this, two planar sections with a common center, rotated by 30° and 60° from the feed direction, were defined on the surface (α and β), on which 7 profiles each were measured equidistantly (Figure 2). The middle points of the profiles recorded in the measurement planes are shown with dots and their coordinates are given in Figure 2. Their base (the origin of the coordinate system) is point α4 = β4. The parameter values set during the measurement and evaluation were given according to the requirements of the ISO 21920:2021 standard.



Profile point	Section α X [mm]	Section α Y	Section β X [mm]	Section β Y
1	-22.5	-13	-13	-22.5
2	-15	-8.67	-8.67	-15
3	-7.5	-4.33	-4.33	-7.5
4	0	0	0	0
5	7.5	4.33	4.33	7.5
6	15	8.67	8.67	15
7	22.5	13	13	22.5

Figure 2 – Measurement points and planes on the milled surface

3. Results and Discussion

The arithmetic mean roughness R_a and maximum profile height R_z values measured at the examined points are summarized in Table 2, which are the arithmetic averages of the results of three measurements. Furthermore, the roughness and waviness profile curves measured at points 1, 3, 5 and 7 of the two sections are shown in Figure 3.

Based on the results presented in Table 2 and Figure 3, we analyze the roughness measured in different parts of the topography and its inhomogeneity along the measurement directions. For this we assume that the milled surface moves in certain directions relative to its counterpart during operation. In this case, a greater part or the whole of the surface determines the friction characteristic. Because of this, we measured and analyzed the roughness at several points of the topography in the measurement directions, then we specify the arithmetic mean ($\overline{R_x}$)in Table 2 and the degree of deviation (ΔR_x) in Table 3 for each direction and parameter according to the formulas below, where $x = a, z$ means the parameter, and i is the number of the measurement point. The latter is expressed by the extent and its percentage compared to the average.

$$\overline{R_x} = \frac{\sum_{i=1}^{7} R_{x,i}}{7}$$

$$\Delta R_x = R_{x,i} - \overline{R_x} \ [\mu m]$$

$$\Delta R_x = \frac{R_{x,i} - \overline{R_x}}{\overline{R_x}} \ [\%]$$

The changes in values of the two examined roughness parameters are almost identical (Figure 4), which means that the measured profiles and the repetition of milling marks is also regular; the ratio of average peak-to-valley height of the profiles and the size of areas below and above the center line are almost the same.

Table 2 – Roughness values in measurement planes

Profile point:		1	2	3	4	5	6	7	$\overline{R}$
Section α	Ra [μm]	1.32	1.37	1.40	1.40	1.38	1.33	1.27	1.35
	Rz [μm]	6.31	6.67	6.85	6.99	6.97	6.79	6.86	6.78
Section β	Ra [μm]	1.21	1.27	1.30	1.26	0.98	0.54	0.79	1.05
	Rz [μm]	6.03	6.32	7.02	6.86	6.77	4.28	6.38	6.24

Based on the data in Table 3, the degree of roughness deviations in plane α is ΔR_a = 0.14 μm (10.2%) and ΔR_z = 0.68 μm (10%), while in plane β it is ΔR_a = 0.76 μm (72.2%) and ΔR_z = 2.74 μm (43.9%). In previous studies, the change in values of the same roughness parameters was minimal (4%) in the symmetry plane (in the feed direction) [22] and was enormous (up to 154%) in the perpendicular direction [23]. It follows that when the angle of the measurement plane (and direction) from the feed vector is increased to 90°, the extent of the differences increases. The degree of deviation shows that the inhomogeneity is still small in the measurement direction at an angle of 30° to the feed, where similar R_a and R_z values can be measured along the studied length. However, at the larger angle of 60° it has become significant.

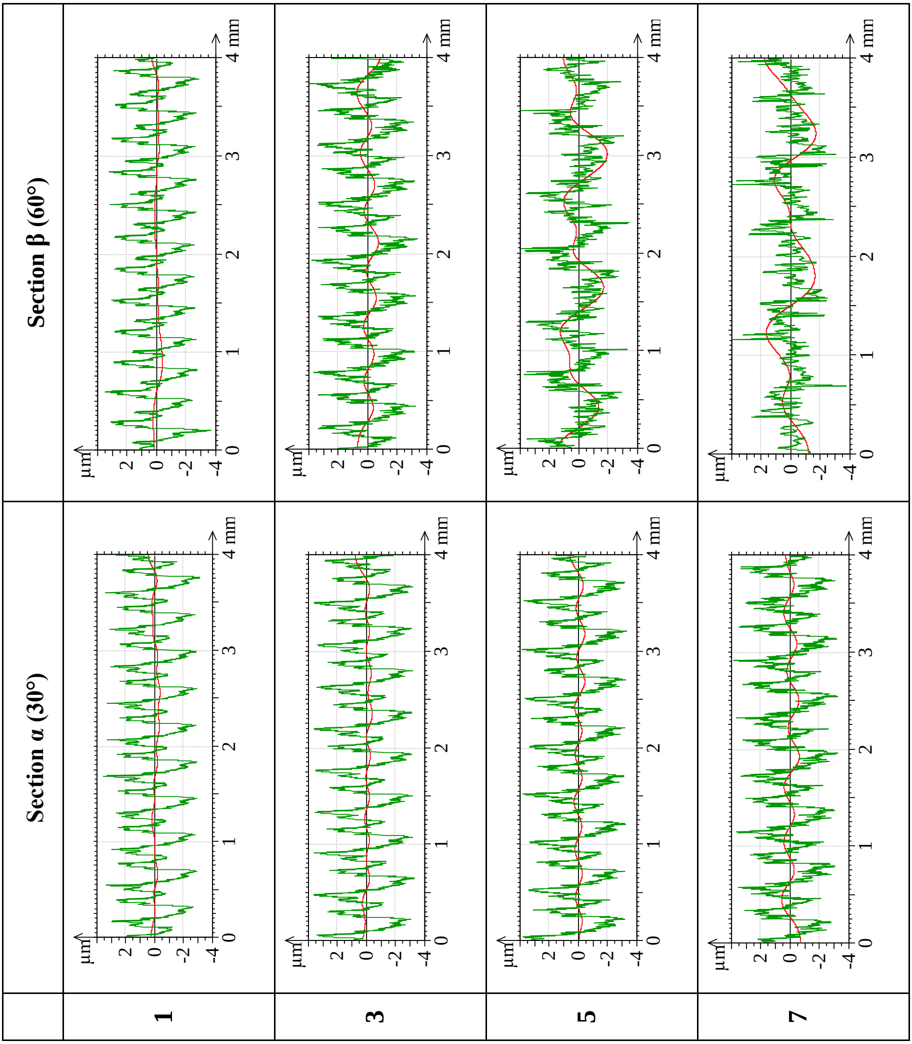


Figure 3 – Roughness and waviness profile curves at several measurement points

Table 3 – Deviations in roughness values in measurement planes

Profile point:		1	2	3	4	5	6	7	ΔR	
Section α	ΔR_a [µm]	-0.037	0.019	0.050	0.051	0.031	-0.027	-0.088	0.138	10.2%
	ΔR_z [µm]	-0.464	-0.110	0.074	0.214	0.195	0.012	0.079	0.678	10.0%
Section β	ΔR_a [µm]	0.157	0.224	0.247	0.209	-0.067	-0.510	-0.261	0.757	72.2%
	ΔR_z [µm]	-0.203	0.079	0.781	0.621	0.534	-1.958	0.146	2.739	43.9%

In plane α, maximum values are found at point 4 (in the vicinity of the symmetry plane), and from this location they decrease in two directions with distance. This feature is in agreement with our previous statement that the roughness values are basically determined by the distance and position of the measurement location from the symmetry plane [23], and also with the observation described by Varga and Kundrak [19]; by moving away from the symmetry plane in two directions, the values of amplitude parameters decrease, if profiles are measured in the feed direction.

Values of points 1–4 show the same character in both planes. However, in plane β significant changes can be observed in other parts (Figure 4). Minimum values measured at point 6 are lower by 49% for R_a and by 31% for R_z than the arithmetic averages given in this section. This is due to the characteristics of the milled topography created by the looped cycloid tool edge path. The milling marks are repeated at the same distance on a profile measured in the feed direction; at any position on the topography, however, the angle between a measurement plane taken in a different direction from the feed and successive cutting marks (see illustration of these in Figure 2) varies, and therefore the width of milling marks measured in the plane also changes. In plane β, the distance between adjacent milling marks increases from point 1 to 6, and at point 6 the measurement plane is almost tangential to the milling edge traces (for this reason, a much smaller profile height can be measured at the set evaluation length), then the width decreases to point 7. The same can be observed in plane α, but in this measurement direction and studied width, its value-changing effect is minimal. By further rotating the measurement plane, e.g. in a direction perpendicular to the feed, we also experienced a deviation of 154% for R_a and 124% for R_z compared to the average of values measured on the surface [23]. Based on the nature of changes in values, it can be concluded that, while in the case of measurements parallel [24] or perpendicular [23] to the feed, the roughness changes in the same way when moving away from the symmetry plane in two directions, when measured in a direction and plane different from the feed, the change in values is not symmetrical to the middle.

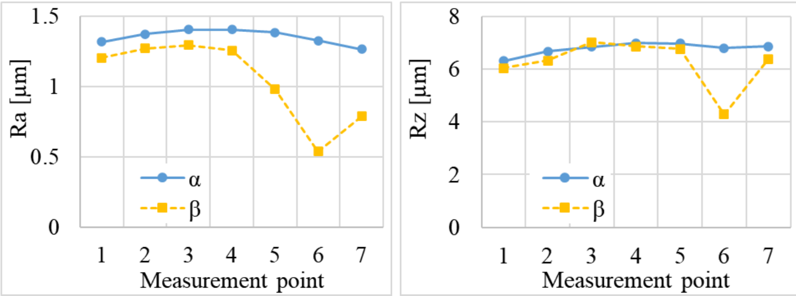


Figure 4 – Roughness values as a function of measurement direction and location

Roughness profile curves are basically determined by the impression of the tool edge on the surface depending on the edge geometry and the feed value. In order to evaluate this, to filter out waviness (e.g. tool, workpiece vibration traces) from the primary profile, it is necessary to choose the appropriate cut-off length value. According to ISO 21920, in case of periodic profiles its value should be taken according to the mean width of the profile elements (milling marks). However, applying the cut-off value for all measurements that is standard for the topography, due to the change in the width of profile elements, the waviness curve will be likely-periodic, its amplitude will increase, and in exchange the roughness peak-to-valley height will decrease on successive profiles along the measurement planes. This means an incorrect filtering method, where evaluated profile heights are displayed that are not accurate. Therefore, it would be useful to clarify the method for the choice of appropriate cut-off length value, taking into account such a case (e.g. in the direction-dependent analysis of face milled topography). This requires further investigations.

5. Conclusions

In this article we investigated the roughness and inhomogeneity of a surface topography face milled with a symmetrical setting in planar sections with an angle of 30° and 60° to the feed direction, assuming that the fitted surface can move relatively in these directions, where the texture is decisive in the friction conditions. During this, we recorded 7 equally spaced profiles in each measurement direction, covering as much length as possible on the surface, in order to analyze the differences in roughness. Our findings are summarized below.

- Minimal deviations were observed in the measurement direction at an angle of 30° from the feed vector, and significant differences in the plane at an angle of 60°. Along with our previous observations, it can be predicted that when the angle of the measurement plane (and direction) from the feed direction is increased to 90°, the degree of deviation will increase.
- The results show that the movement of the fitted surface during operation in a direction different from the feed by 30° may not change the friction conditions remarkably; however, the increase of the angle to 60° may cause significant changes.
- In plane α, the nature of the change in values was mainly determined by the distance of measurement position from the symmetry plane, where the values of amplitude parameters decreased slightly with distance from it.
- In the direction with a larger angle, the size of the angle between the measurement plane and the direction of milling marks had a dominant effect on the high degree of inhomogeneity. The profile height was minimal in a position where the measuring plane was almost tangential to the cutting trace.
- In measurement directions other than the direction of feed, the width of milling marks always changes. As a result, when the same cut-off length value was set, the waviness curve became likely-periodic along the measurement directions and the evaluated profile curves were characterized by heights different from the real ones. In order to choose the appropriate evaluation conditions, further tests are required to refine the method.

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ДОСЛІДЖЕННЯ РЕЛЬФЕРУ ТОРЦЕВОГО ФРЕЗЕРУВАННЯ НА ЗАГОТІВЦІ C45 ПРИ ПЕРЕМІЩЕННІ НА 30° ТА 60° В НАПРЯМКУ ПОДАЧІ

Анотація. *У цій статті автори досліджували шорсткість і неоднорідність рельєфу поверхні, відфрезерованої з симетричною установкою в плоских перерізах під кутом 30° і 60° до напрямку подачі, припускаючи, що підігнана поверхня може рухатися відносно в цих напрямках, де текстура є вирішальною в умовах тертя. Під час цього автори записали 7 рівновіддалених профілів у кожному напрямку вимірювання, охоплюючи якомога більшу довжину поверхні, щоб проаналізувати різницю в шорсткості. Мінімальні відхилення спостерігалися авторами в напрямку вимірювання під кутом 30° від вектора подачі, а значні розбіжності в площині під кутом 60°. Поряд з попередніми спостереженнями, можна передбачити, що коли кут площини вимірювання (і напрямку) від напрямку подачі збільшується до 90°, ступінь відхилення збільшиться. Результати показують, що переміщення підігнаної поверхні під час роботи в напрямку, що відрізняється від подачі на 30°, може не значно змінити умови тертя; однак збільшення кута до 60° може викликати значні зміни. У площині α характер зміни значень визначався в основному віддаленістю місця вимірювання від площини симетрії, де значення амплітудних параметрів дещо зменшувалися з віддаленням від неї. У напрямку з більшим кутом величина кута між площиною вимірювання та напрямком сліду від фрезерування мала* *домінуючий вплив на високий ступінь неоднорідності. Висота профілю була мінімальною в положенні, де площина вимірювання була майже дотичною до сліду різання. У напрямках вимірювання, відмінних від напрямку подачі, ширина слідів фрезерування завжди змінюється. У результаті, коли було встановлено те саме значення граничної довжини, крива хвилястості стала ймовірно періодичною вздовж напрямків вимірювання, а оцінювані профільні криві характеризувались висотами, відмінними від реальних. Для того, щоб вибрати відповідні умови оцінки, необхідні додаткові дослідження для вдосконалення методу.*

Ключові слова: *торцеве фрезерування; шорсткість поверхні; розподіл шорсткості; залежна від напрямку характеристика топографії.*