Influence of the feed rate on the workpiece surface in face milling

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Abstract: Because of the diversity of cutting processes, the created tools imprints on the surfaces – which affect the formation of the topography – can take many forms. Besides this, roughness values of machined surfaces are different along the path of the cutting edge and when measured at different directions of the surface of the workpiece at face milling due to the special movement of the tool, therefore the knowledge of and the ability to plan the roughness characteristics of the surface are extremely important. Here, topography of face milled surface is studied with theoretical and experimental methods. The investigations covered the determination of 2D and 3D theoretical values of roughness indexes using a method developed by the authors, and the completion of cutting experiments and analysis of roughness of the obtained machined surfaces. The results obtained by modeling were compared with measurement data from the machined surfaces. In this publication, results of surface analysis when cutting with one and two circular inserts are introduced. The tests were performed by varying the value of the feed per tooth (f_z) and the effect of the increase of f_z on surface roughness characteristics (topography) were analyzed.

Key-Words: - Face Milling, Surface Roughness, 2D and 3D Roughness Parameters

1 Introduction

The investigation of micro-geometrical properties of surface topographies which can be generated by the different cutting procedures and their roughness indexes have long been and continuously are important directions of research. This is due to tthe accuracy and quality requirements for built-in parts constantly becoming more stringent. In order to fulfill these requirements, it is necessary to better understand the topography which corresponds to the working conditions, and to finish machine surfaces in a way that takes it into consideration in order to significantly extend the lifespan of machined parts.

This is not an easy task, as the surface topography generated during machining is becoming more diverse, since with the development of cutting procedures, beside the kinematical differences, more and more diverse solutions are created for the design of the applied cutting tools. In addition, the positioning of the cutting edges in one tool body and their edge geometries also vary. Thus, the topography of cut surfaces can vary widely, and therefore the effect of the generated topography on the tribological properties of functional surfaces can be very different. In addition, the knowledge of the expected roughness after machining is also important because one of the roughness indexes (which is prescribed on the part drawing) of machined surfaces is often considered to be the criterion for the permitted extent of tool wear in finishing machining. Because of the above-mentioned reasons, an emphasized aim in the planning of finish machining is to be able to plan and to select the optimal values of as many as possible of the characteristics of produced parts determining their accuracy and quality. The applied modeling techniques have been summarized in the literature. According to [1], the modeling techniques applied by researchers can be classified as follows: analytical models; experimental methods; models that utilize designed experimental methods; and procedures that are based on artificial intelligence. Roughness investigations and their results have been extensively presented in the literature in the recent years, too.

A modeling method is introduced in [2] which is based on a geometrical analysis of the re-creation of the tool trail left on the machined surface. During the modeling, particular attention was paid to consideration of the tool setting errors (axial and radial). Not only the theoretical values were determined with the help of the developed procedure, but two-dimensional theoretical roughness profiles were also produced. A grey-fuzzy modelling method was applied in [3] for the determination of the optimal process parameters for end milling of an aluminium alloy. The investigated process parameters were the Center Line Average Roughness (Ra), the Root Mean Square Roughness (Rq) and the Material Removal Rate (MRR). A hybrid approach is presented for the modeling of surface roughness in slot milling in [4], where the analytical calculation of the specific energy consumption (SCEC) and empirical relations between the SCEC and surface roughness are combined is one model. It was found that a direct connection can be revealed between the specific energy consumption (which is the cutting power required to remove 1 mm^3 of workpiece material) and the Ra roughness parameter, thus a new model was proposed for the prediction of the expected roughness. Effects of such technological parameters as spindle speed, feed and depth of cut on the roughness, flatness and form control of machined surfaces were analyzed experimentally in [5] using ANOVA for the face milling of wrought cast steel (WCB grade B) workpieces. FEM modeling was applied in [6] in order to investigate the effects of feed on surface roughness (Ra) and components of cutting force (F_c, F_f) for face milling of a titanium alloy. During the modeling and the performed experiments, it was found that the prediction of the expected roughness can be done on the basis of the described equation with the feed directional force component obtained by FEM modeling. Investigation of the relations between technological parameters (cutting speed, feed rate, axial and radial depth of cut) and integrity of machined surfaces (roughness, topography, microhardness, white layer thickness and chemical composition of the surface) was conducted in [7] using the response surface methodology (RSM) method for hard milling of 4340 alloy steel when only a minimal quantity of lubricant is applied. It was found that the increase of the cutting speed decreases the surface errors, and the increase of any of the investigated parameters will increase the micro-hardness and the white layer thickness. Theoretical description of the surface pattern which evolves in face milling is performed in [8], where both mathematical calculations (MATLAB) and CAD simulations were utilized to investigate the effects of the various workpiece and tool designs and positions, the feed and the angle between the milling axis and the machined surface on the quality (roughness) of the machined surface. Authors of [9] investigated the effects of the up- and down-milling method and the changing of technological parameters on surface roughness in case of milling thin-walled workpieces by an analytical modeling method. RSM was utilized in [10] to analyze the effects of the cooling and lubricant, technological data (spindle speed, feed rate and depth of cut) and the milling method (up- or down-milling) on residual stresses, cutting forces and roughness of machined surfaces. Not only the cutting parameters and the axial and radial setting errors were considered in the surface prediction method, which is presented in [11], but also the dynamical phenomena that result from the cutting tool deflections in case of end milling. In [12], the focus is on the determination of optimal cutting parameters that result in minimal roughness characteristics at up peripheral milling, where the estimation of theoretical parameters was performed by a model utilizing an Artificial Neural Network (ANN). The input and output parameters were determined by RSM and ANOVA methods. The experiments for training and for validation were performed by machining of Ti-6Al-4V ELI alloys.

It can be seen from this short review that the research activities are very diverse. In this paper a CAD-modeling-aided definition of theoretical profiles of milled surfaces is introduced that is a multi-purpose solution for the prediction of the expected roughness and for the determination of theoretical indexes by defining/revealing their connections with real indexes. Cutting experiments were performed and their results are introduced for face milling with circular inserts. During the investigations, the changing of the topography was analyzed as a function of the feed per tooth, along constant depth per cut. This was chosen because in recent years efforts are being made to minimize the allowance of workpieces, so that the blank is as close to the final dimensions as possible, which can be removed in one cut. At the end of the article, the 2D and 3D measured data and theoretical values determined by modeling are compared.

2 Experimental setup

The goal of the experiments was to analyze the change in the topography caused by the variation of the feed for milling by circular inserts.

2.1 Work material, cutting tools and cutting parameters

Workpiece: The material of the workpiece was 42CrMo4 alloyed heat treatable steel. The workpiece material was in quenched and tempered state, the tensile strength was 1080 N/mm2, and its hardness was 320 HB. The specimens were formed as 50x50x100 mm blocks.

Machine tool: The milling machine was a Maho MH 600 E type vertical milling machine with Philips CNC 432 control.

Cutting tool: The milling head was a special milling cutter developed at the Otto-von-Guericke University in Magdeburg [8]. This special milling head is equipped with cylindrical shaft-type cutting insert holders. Its outer diameter is ∅80 mm, while the effective (working) diameter depends on the type of the applied cylindrical shank and insert. It was clamped to the machine spindle by an SK 40 quick release taper.

LMT FETTE RCKX 1606MO-TR LC240T circular milling inserts were utilized during the test. The tests were conducted using a single insert (fly-cutting) at first and then by using two identical circular inserts simultaneously.

Cutting data: The applied technological data were as follows:

- Cutting speed: v_c = 100 m / min
- Depth of cut: a_p = 1 mm
- width of cut: a_e = 50 mm
- The varied parameter was the feed per tooth (and hence the feed rate): f_{z1} = 0.2127; f_{z2} = 0.638; f_{z3} = 1.06; f_{z4} = 1.48; f_{z5} = 1.915

2.2 The process of carrying out of the cutting experiments

During the experiments, at first only one insert was fixed onto the milling head, and after that, two identical inserts were used. While generally more than one insert is used in milling heads, the aim of that decision was to investigate the effects of two inserts on the surface if they have setting errors (in axial and radial directions) to each other.

The axial deviation of the inserts was 65 µm in the conducted experiments, while the radial deviation was kept at "0" value (the setting errors were measured around the accuracy of the applied Zoller V420 tool pre-setter equipment at 1~2 µm), so it was not considered in the calculations.

The modeling and calculations were performed for all cutting data combinations as well as the cutting experiments and the roughness measurements on cut surfaces.

Cutting experiments were performed with the planned experimental data and 2D and 3D roughness were measured on machined surfaces while the theoretical profiles were created using a method developed by the authors (CAD modeling), and theoretical roughness values were also calculated.

2.2.1 Measurement of roughness of face milled surfaces

The two- and three-dimensional roughness measurement of the machined surfaces was performed at the University of Miskolc by an AltiSurf 520 three-dimensional surface roughness measurement station. A CL2 confocal chromatic probe was used for the surface roughness measurements, with an MG140 magnifier. Thus, an axial resolution of 0.012 µm could be achieved. The lateral resolution of this equipment is 0.5 µm, which is adequate for this type of investigation. The measurement range of this probe is 300 µm, which has proved to be suitable for the investigations. The utilized measurement parameters were as per ISO 4287 and 4288 standards for profiles and ISO 25178 for areal measurements.

2.2.2 Modeling and calculation of theoretical values of roughness

The main steps of the CAD-based modeling method [13] applied for the determination of theoretical roughness indexes of face milled surfaces were the following (see Fig. 1).

The essence of the method is to create a three-dimensional model of the machined surface in an expediently selected CAD system, and then to query its points with a specified accuracy to a file with the help of a developed interface program. This mathematical point representation of the surface can be later processed by surface topography analysis software, and the theoretical roughness indexes can be evaluated.

The first step of the elaborated method is to create the three-dimensional model of the machined surface in the selected CAD system. In the actual investigations, the Autodesk Inventor software was applied. During the modeling, the blank (raw) part was created at first, which is a prism in the investigated machining method. The description of the tool was the next step, which was performed as follows: the two-dimensional section of the cutting insert shape was drawn in the tool reference plane. After that the trajectory of the cutting insert was created in the assumed work plane. To do this, the parametric form equation of the curtate cycloid curve path of the tool pitch point (i.e. the intersection point of the major and minor cutting edges) was utilized. The previously drawn cutting insert shape was guided along this generated tool path and thus the swept volume of the single insert during one tool rotation was achieved. The theoretical chip volume can be generated by cutting out this volume from the model of the workpiece. This procedure should be repeated for every cutting insert, and here it is also possible to take the axial and radial setting errors between individual inserts into consideration. The generated theoretical chip volumes were multiplied in the surface according to the feed per tooth value, and thus the model of the machined surface was obtained.

For the determination of theoretical roughness, points of the obtained theoretical cut surface should be queried from the CAD system with the given accuracy and then these should be saved in an expediently chosen file format (SURF format by Digital Surf Inc.) for which a special interface program has been developed. This file can be processed by the AltiMap evaluation software of the AltiSurf 520 surface topography analyzer equipment, performing the evaluation according to arbitrary two and three-dimensional roughness parameters as well as by the determination of theoretical roughness characteristics.

A great advantage of the developed method is that the theoretical and real roughness data are evaluated on the same basis, by using the same software, and therefore can be precisely compared.

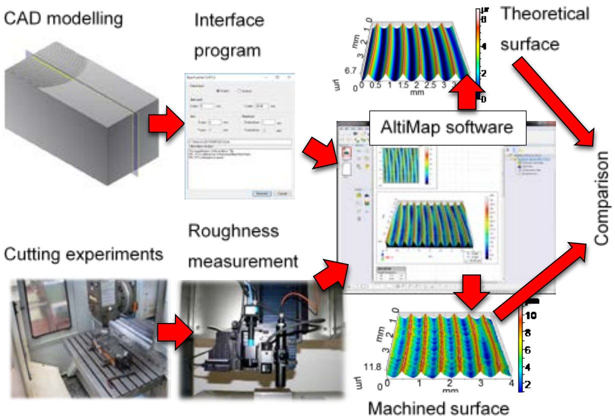


Fig. 1
The investigation method

3. Results

The tests were performed with the experimental data, by increasing the feed per tooth f_z from 0.21 mm/rev. to 1.92 mm/rev in five steps. As constant depth per cut was applied (a_p = 1 mm), the a_p/f_z ratio was varied between 4.76–0.52 at the investigated feed domain. Profile diagrams were created from the cut surfaces and the 2D and 3D roughness characteristics were measured. The CAD model was created for the determination of theoretical values of indexes, which shows the theoretical profile of a surface milled by a circular insert (Fig. 2.). It can be seen that the tool marks and thus the roughness values change significantly if different measurement planes are considered. The actual investigations were performed in Plane 1, at the middle line of the workpiece (at the centerline of the cutting tool in feed direction). However, the model is suitable for the determination of theoretical values of all standard roughness parameters.

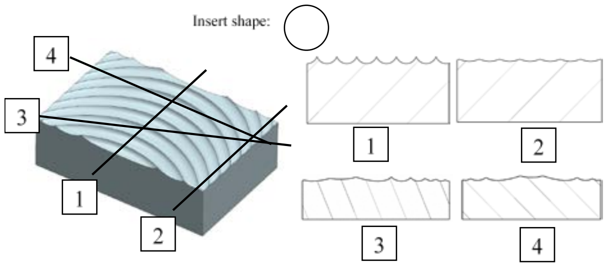


Fig. 2.
Changing of the theoretical profile on a face milled surface in different measurement lines

The results of investigations for the Ra, Rz, Rt, Sa and Sz roughness parameter are given. The theoretical values which were calculated using model and the measured 2D and 3D roughness data on cut surfaces for cutting with one and two circular inserts are summarized in Table 1 and in Table 2.

Results of machining by one insert are introduced in Figs. 3-5, while the results of machining by two inserts are shown in Figs. 6-8.

Table 1
2D Roughness parameters for different feed values

f_z, mm	a_p/f_z	2D roughness, μm			
		Insert			
		Theo.	Meas.	Theo.	Meas.
0.21	4.76	Ra = 0.17 Rz = 0.69 Rt = 0.69	Ra = 0.11 Rz = 0.66 Rt = 1.18	Ra = 0.7 Rz = 2.76 Rt = 2.76	Ra = 1.13 Rz = 6.09 Rt = 7.14
0.64	1.56	Ra = 1.63 Rz = 6.4 Rt = 6.4	Ra = 2 Rz = 9.23 Rt = 9.86	Ra = 6.57 Rz = 25.64 Rt = 25.64	Ra = 6.48 Rz = 26.76 Rt = 27.86
1.06	≈1	Ra = 4.49 Rz = 17.58 Rt = 17.58	Ra = 4.95 Rz = 19.5 Rt = 20.45	Ra = 18 Rz = 65.11 Rt = 65.11	Ra = 17.67 Rz = 73.87 Rt = 73.89
1.48	0.68	Ra = 8.71 Rz = 34.3 Rt = 34.3	Ra = 8.83 Rz = 38.32 Rt = 38.67	Ra = 24.6 Rz = 74.53 Rt = 74.53	Ra = 22.88 Rz = 79.41 Rt = 84.84
1.92	0.52	Ra = 14.85 Rz = 57.81 Rt = 57.81	Ra = 14.4 Rz = 59.57 Rt = 61.85	Ra = 28.5 Rz = 94.92 Rt = 94.92	Ra = 27.83 Rz = 98.17 Rt = 102.6

Table 2
3D Roughness parameters at milling with two inserts

f_z, mm	a_p/f_z	3D roughness, µm			
		Insert (one)		(two)	
		Theo.	Meas.	Theo.	Meas.
0.21	4.76	Sa = 0.18 Sz = 0.69	Sa = 1.07 Sz = 8.5	Sa = 0.7 Sz = 2.76	Sa = 1.23 Sz = 9.7
0.64	1.56	Sa = 1.62 Sz = 6.4	Sa = 1.98 Sz = 11.85	Sa = 6.56 Sz = 25.64	Sa = 6.19 Sz = 31.39
1.06	≈1	Sa = 4.51 Sz = 17.58	Sa = 4.92 Sz = 25.79	Sa = 17.8 Sz = 65.11	Sa = 17.77 Sz = 84.62
1.48	0.68	Sa = 8.96 Sz = 34.3	Sa = 8.85 Sz = 41.76	Sa = 23.72 Sz = 74.53	Sa = 24.72 Sz = 95.97
1.92	0.52	Sa = 14.82 Sz = 57.81	Sa = 13.54 Sz = 69.8	Sa = 29.37 Sz = 94.92	Sa = 26.57 Sz = 102.31

4. Evaluation and Discussion

The evaluation of experimental results was conducted on the basis of the analysis and comparison of profile diagrams (two- and three-dimensional roughness profiles) of surfaces and the calculated theoretical values of their roughness indexes.

4.1. Experiments with one insert

First the exhibited characteristics of a surface created by the rotation of one insert were analyzed. The change of the feed significantly affects the roughness characteristics of the surface. Both the experimental and calculated results show that increasing the feed (thus the decrease of the a_p/f_z ratio) leads to a significant, exponential increase in the roughness in all cases. The nine-fold increase in the feed resulted in the increase of the roughness values by Ra*128, Rz*90, Rt*52 respectively. However, it is clear from the table values that theoretical roughness indexes closely follow the change of the real roughness.

It can be also stated from the analysis of surface profiles that the theoretical profile shows the periodic nature of the surface, and the change of the roughness profile can be easily followed as a function of the feed. In addition, it can be well seen in the case of using one circular insert (Fig. 3) that both the profiles and theoretical and real values of roughness show very good agreement. It can be also concluded at the analysis of profiles that the correspondence between theoretical and real profile improves as the feed increases. This can be attributed to the fact that effects of other chip removal characteristics are proportionally more significant at low feeds compared to the geometrical characteristics that were used to create the CAD model.

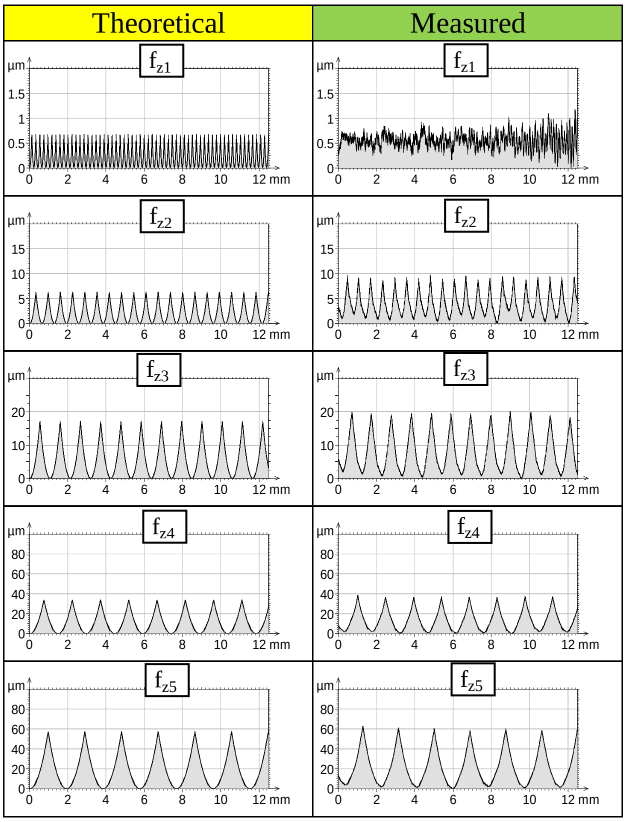


Fig. 3
Theoretical and measured 2D profile diagrams of surfaces milled with one circular insert

The shape of the theoretical profile, the periodic nature of the surface and the character of growing of the roughness with the increase of the feed is clearly visible from the 3D profile diagrams (Fig. 4). The tool mark is less regular at the smallest feed, as the effects of the transitions occurring at the chip root and the extent of the changes are closer to the dimensions of the imprints. While the modeled surface exhibits very good agreement with the machined surface, it can be also concluded that the dynamic effects on cut surfaces can be tracked more easily at low feeds. By comparing the measured and calculated values (Fig. 4) it can be stated that the model is suitable for the determination of the theoretical value of roughness, and it well follows the real roughness.

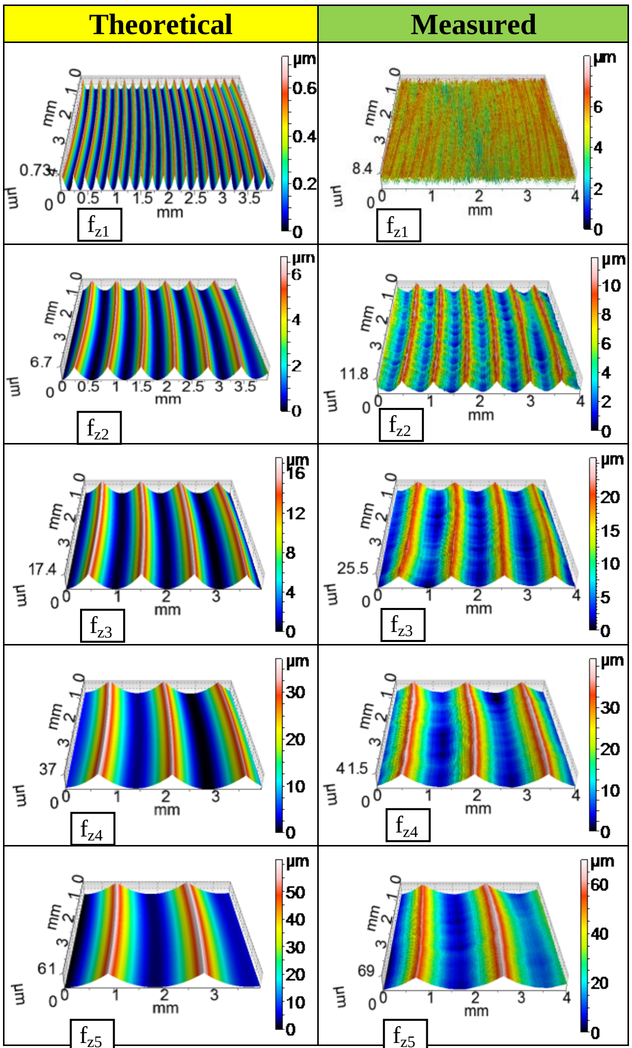


Fig. 4
Theoretical and measured 3D surface diagrams of surfaces milled with one circular insert

The measured theoretical and the real roughness values are introduced in Fig. 5 as along with their character of change as a function of feed. Measured and calculated values of Ra are nearly the same, while theoretical values of Rz are slightly lower than the measured values. A similar statement can be made for the Sa and Sz values, with the remark that the theoretical value of Sz is approximately 20% smaller than the real value.

It can be concluded that the theoretical roughness values determined by the model show good agreement with the measured values both in the character of change and in the values themselves. It can be stated from the figures that the accuracy of the values calculated by the model is sufficient to predict the actual roughness.

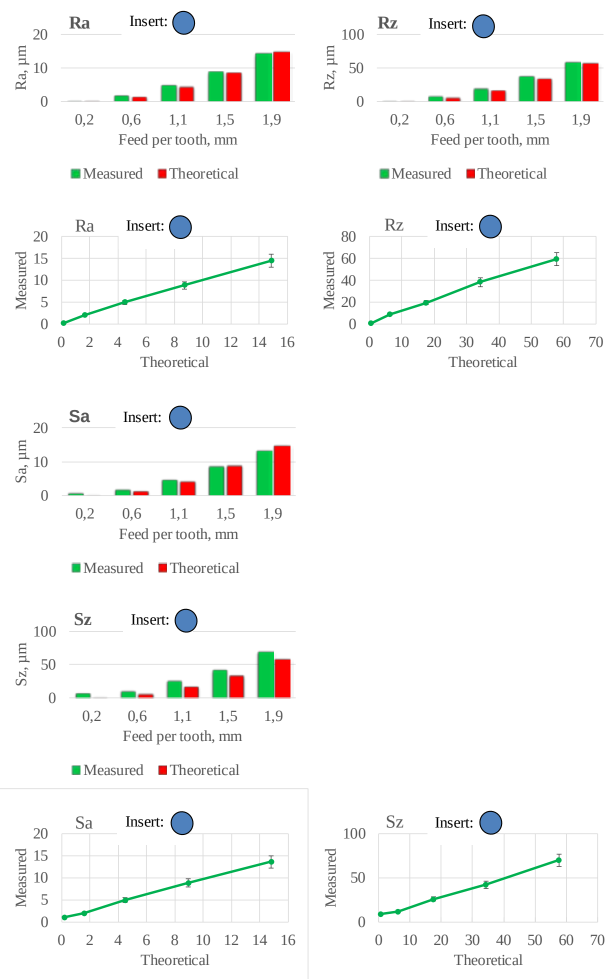


Fig. 5
Roughness characteristics of surfaces milled by one circular insert as a function of the feed

4.2 Experiments with two circular inserts

When two cutting inserts were applied, differences were experienced during the analysis of the profile diagrams of cut surfaces with the same feed per tooth values compared to surface machined by one insert (Fig. 6). If two or more inserts could be fixed without setting errors, then about the same profile should be produced for the same feed per one edge as in milling by one insert. The reason for the deviation is the previously introduced setting error, which naturally affects the topography of cut surface. The two circular inserts were located in the milling head with a difference between them of e_{ax} = 65 µm value. The topography of the cut surface was changed by this fact. Roughness values were increased with the same feed per tooth values. The reason for this is that the insert that is located farther away from the surface is not working at low feed values because of the axial setting error, while at higher feeds it still removes a smaller chip cross section than the adjusted value. The degradation of the surface roughness is significant because of this error. There are 2-10X differences between the measured values, and the difference is bigger at lower feeds. These differences show the particular importance of the tool edge setting. The consideration of setting errors is also important because the dynamical conditions of cutting are altered, and the imprints of the tool edge shifted towards each other with the setting error value. It can be seen on the profile diagram (Fig. 5) that the difference between theoretical and real roughness is the greatest at the lowest feed. The correspondence between theoretical and real data is good at the next to feed values, but only one insert edge has formed the surface at these cases. It is easy to follow as the second insert starts to cut at higher feeds, but it removes significantly smaller chip cross section. Practically, chip removal was performed only with feed per tooth values of f_z = 1.48 and 1.98 mm by both inserts. While only one insert is cutting, it is practically working with two-fold feed values per the set data, therefore there are significant differences in roughness values at lower feeds. The developed CAD model was extended to be able to determine theoretical roughness values of resulting topographies in such cases, too, as can be seen on the profile diagrams. While the inserts always have some extent of setting errors, it is an important advantage that the model can take these deviations into consideration.

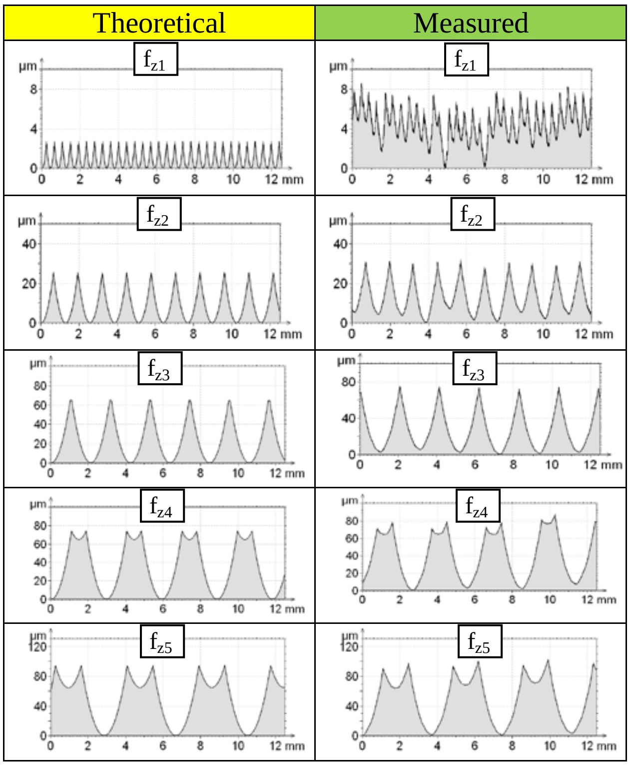


Fig. 6
Theoretical and measured 2D profile diagrams of surfaces milled with two circular inserts

Three-dimensional profile diagrams of theoretical and real surfaces are shown in Fig. 7. It was found that the theoretical profile clearly follows the real one in that case, too.

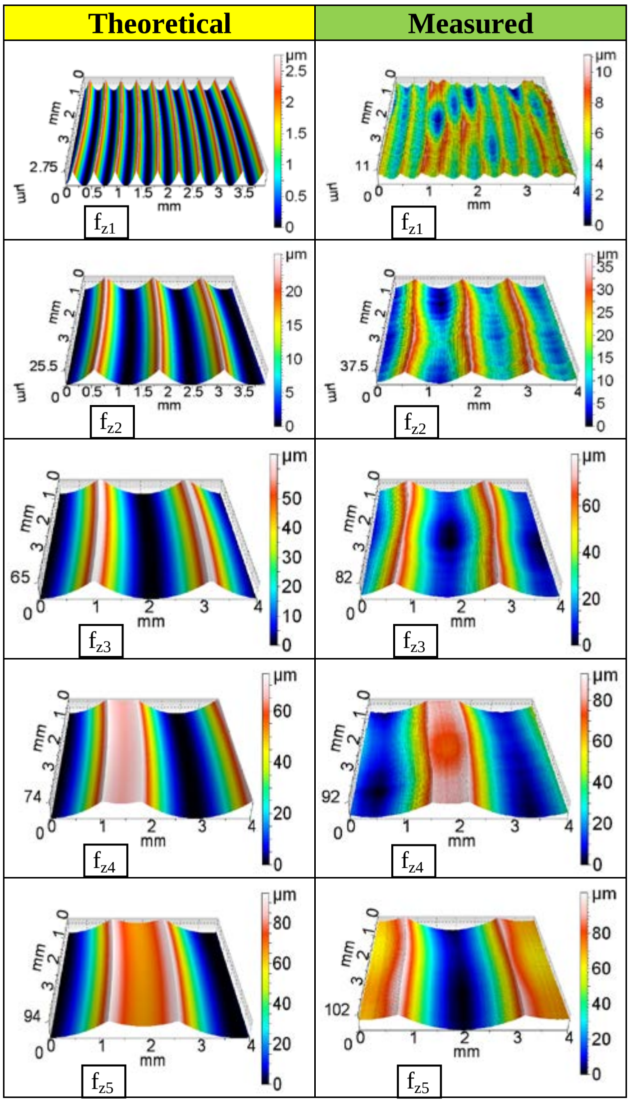
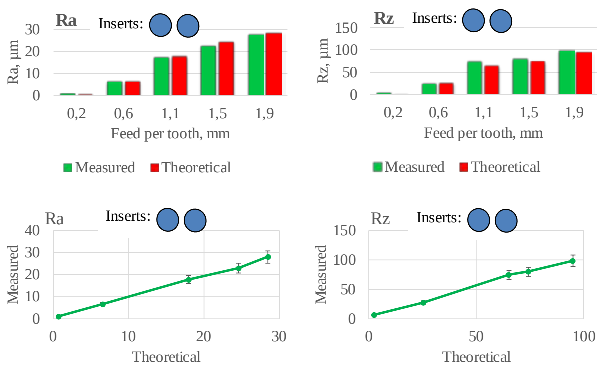


Fig. 7
Theoretical and measured 3D surface diagrams of surfaces milled with two circular inserts

Findings from the comparison of theoretical and real roughness values of surfaces machined by two insertsare similar to those when cutting by one insert. The easy-to-follow connection between the two vales (Fig. 8) can be attributed to the applied model considering the setting errors precisely.



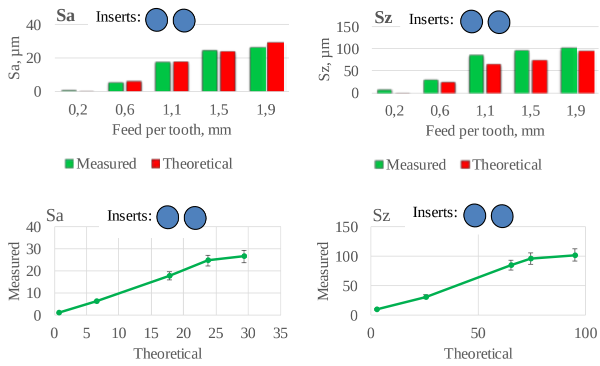


Fig. 8
Roughness characteristics of surfaces milled by two circular inserts as a function of the feed

5. Conclusions

The creation of blank parts with as minimal allowance as possible (near net shape) is a significant challenge in production engineering. The aim is to be removed the blank part in one cut during the machining of the part. This fact makes the investigation of the feed increasingly important. Two effects of the increasing of the feed value should be highlighted: the efficiency of the material removal increases but the roughness of the surface will also increase. Since this is the final machining in most cases, the prescribed roughness values should be ensured here, and it can be a limit for the increasing of the feed. The consideration of this is extremely important, as the final formation of surfaces ensuring the functional conditions are performed in the finishing operations.

The influence of the changing of the feed on roughness indexes was presented for face milled surfaces. Roughness data of surfaces which were milled with identical cutting parameters were analyzed and compared with theoretical values calculated by the CAD model and calculation method developed by the authors. In addition to the calculation of 2D and 3D theoretical roughness values, the model is suitable for displaying theoretical profiles. It can be stated from the results of the experiments that the theoretical 2D and 3D roughness profiles exhibit good correlation with the profiles of cut surfaces.

In the case of a nearly ten-fold change in a_p/f_z values, the theoretical roughness values and their change follow the real roughness values with good correlation. Effects of setting errors were introduced with the experiments with two inserts. It was found that the axial setting error of the insert can significantly influence the roughness of the surface, which requires strict tool measurement regulations.

Finally, it can be concluded that the methodthat was applied in the investigations is an effective tool for the prediction of the expected roughness of milled surfaces.

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