Effect of the Changing of the Feed on Surface Topography at Face Milling

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Abstract: - Topography of surfaces machined by face milling is studied in the paper with theoretical and experimental methods. Roughness of surfaces which were generated by the combination of the rotational and the feed-directional motion of the tool are different in different directions and it also varies when measured in the same direction but in parallel planes. Theoretical values of roughness indexes were determined by a CAD model which considers these phenomena. Cutting tests were conducted with circular inserts, and two- and three-dimensional roughness values are introduced as a function of the feed. The theoretical and real values are compared.

Key-Words: - Face Milling, Roughness, Effect of the Feed

1 Introduction

During the planning of finishing machining, in addition to ensuring the economy and reliability of manufacturing processes, technologists aim to ensure the ability to plan as many characteristics of machined parts –their accuracy and quality – as possible to ensure compliance with operational requirements, and to select optional values. This is the case regarding the microgeometry of machined surfaces, because the generated topography has a significant impact on tribological properties of functional surfaces. Therefore, research continues in analyzing the topography of surfaces, making great demands on research capacity all around the world.

Lu [1] made a classification of the different surface roughness modelling methods based on the review article by Benardos and Vosniakos [2]. In this article, the applied techniques were arranged into three groups: 1) pure modelling; 2) signal-based approaches and 3) artificial intelligence-methods. Some new results are introduced below from the many studies dealing with the determination of theoretical surface roughness which have been published since the previously mentioned review papers.

A new and innovative method for regular structuring and special patterning of a workpiece surface applying face milling process is presented in [3], in which both the machining parameters are set up, as well as cutting tool geometry being considered at the same time. The model for the geometry of the cutting tool was first developed and subsequently a new simulation model for surface pattern by face milling process was established. The authors stated that the results of simulation could be used to optimize the actual face milling process and to improve the workpiece surface quality or predict the surface pattern by the given milling parameters.

Effects of the runout of milling cutter teeth on surface topography, surface location error and stability was investigated in [4]. The authors conclude that runout in milling remains an important issue, because it affects the machining process significantly and can lead to premature failure of the cutting edges. Experimental tests were performed with different amounts of radial runout and the results are compared with a comprehensive time-domain simulation.

A triangle mesh representation of tools cutting a workpiece model is presented in [5], introducing a complex geometric-kinematic milling simulation system. This allows the prediction of surface location errors resulting from the dynamic behavior of the milling tools. The CSG modeling technique is used by the authors to model the tool shape and the material removal is simulated by removing the intersecting volume with the tool from both workpiece models. It was found that the proposed approach is suitable to predict the occurrence of chatter-affected regions in the milling process as well as the machined surface topography.

A geometrical model was introduced in [6] for the prediction of surface roughness in face milling with square inserts. The introduced model is based on a

geometrical analysis of the re-creation of the tool trail left on the machined surface. The model was validated by high speed face milling experiments using an aluminum alloy (Al 7075-T7351). The authors concluded that their model is suitable to predict the surface roughness for any combination of material workpiece and tool with excellent performance, when tool flank wear is not considered.

During such investigations it should be considered that the development of cutting procedures means that the formed kinematics on machine tools, the design of the applied cutting tools and the edge geometry and positioning of cuttings inserts in one tool body results in more and more procedure variants, and thus the topography of cut surfaces is becoming ever more diverse. This is also typical for face milling, if just the high feed rate procedure or the application of inserts having different edge geometries in one milling head is considered. Characteristics of face milling are the path of the tool edge, which describes a cycloid due to the rotational and feed-directional motion of the tool, and that chip removal is influenced not only by the number of cutting inserts but by the number of the simultaneously cutting edges (which are on cut), by the tilt angle of the tool, by the relative positions of the workpiece and the tool, by the width of the workpiece, etc.

The knowledge of the surface topography and its accurate description is the prerequisite for the planning of roughness characteristics of surfaces generated by machining.

Another consideration in cutting is achieving a situation in which the dimensions of the blank of the part are as close to the final dimensions as possible, as this has the minimum allowance (near net shape). In that case, the goal is not the maximization of the Material Removal Rate (MRR), but the Surface Rate (SR), that is to utilize the maximal feed among a constant depth of cut (a_p = const.).

Because productivity can be raised by increasing feed, but at the same time surface roughness deteriorates, it is important to learn more about the effects of feed on surface roughness. Effective prediction can help in determining practical limits on the increase of feed.

In this paper, a definition of the theoretical profiles of milled surfaces is utilized that provides a manageable and multi-targeted solution for the prediction of the expected roughness based on the determination of theoretical indexes and by revealing the connections with real indexes. The effect of the feed was analyzed because the application of increased feed in milling is becoming more common. Cutting experiments are introduced together with the measured roughness results for milling, and measured results and calculated theoretical values are compared.

2 Experiments

The goal of the experiments is to analyze the effect of feed on the roughness of milled surfaces. The investigation is performed based on theoretical values of roughness characteristics and on the real roughness of surfaces machined during the performed cutting experiments [7].

2.1 Experimental conditions

The applied milling machine was a Maho MH 600 E type vertical milling machine with Philips CNC 432 control. The milling head was a special milling cutter which was 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 $\varnothing 80$ 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 experiments. The tests were conducted using a single insert (fly-cutting) at first and then using two identical circular inserts simultaneously. The two inserts were placed symmetrically in the cutting head.

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/mm^2, and its hardness was 320 HB. The specimens were formed as 50x50x100 mm blocks. 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: f_z = 0.2127; 0.638; 1.06; 1.48; 1.915

These feed per tooth values results different a_p/f_z ratios, and therefore different chip forms as it can be seen from the data in Table 1.

Table 1
The used feed per tooth values and the
corresponding a_p/f_z ratios

Notation	Feed per tooth, [mm]	a_p/f_z ratio
f_{z1}	0.2127	4.76
f_{z2}	0.638	1.56
f_{z3}	1.06	≈ 1
f_{z4}	1.48	0.68
f_{z5}	1.915	0.52

2.2 Investigation and measurement method

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

2.2.1 Measurement of roughness

The two- and three-dimensional roughness measurement of the machined surfaces was performed at the University of Miskolc by the 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 The method for determination of theoretical roughness characteristics

The CAD-based modeling of rotary tool was conducted as follows (see Fig. 1).

At first, the three-dimensional model of the workpiece was prepared. The workpiece is a prismatic part in the investigated face milling process, so it was modeled by a simple prism. After that, the two-dimensional projection of the cutting part of the tool was drawn in the axial section of the milling tool (which is the tool reference plane). The description of the trajectory of the cutting insert – a curtate cycloid curve -- was conducted at the next step. The two-dimensional cutting insert shape was guided along this trajectory, thus giving the volume scrubbed by the tool, and its intersection with the solid model of the workpiece gives the cut chip volume. In case of multi-point tools, this procedure

should be repeated for every insert. There is also a possibility to take the radial and axial differences between inserts into account (tool setting errors) by defining the shift values in the respective directions. A model of the machined workpiece can be obtained by subtracting the resulted chip volumes from the workpiece model.

In the next step, points of the modeled machined surface had to be queried from the CAD system with the given accuracy, and these points had to be stored in a suitable form for the evaluation, and for determination of theoretical roughness characteristics. An interface program was developed for this purpose, which can communicate with the CAD system while also saving the points in a convenient file format. A measurement plane was defined in the model, the intersection of which with the machined surface of the workpiece creates the curves that are the theoretical profile curves. Points of these curves were queried with x and y steps, which can be set on the user interface of the developed program, and then the points were stored in a file in SURF file format.
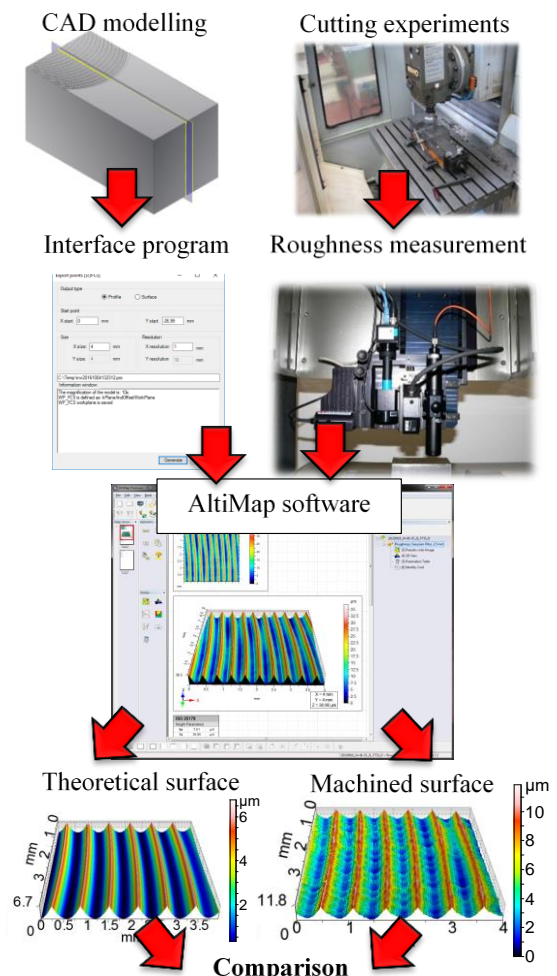

Fig. 1
The applied investigation method

This file can be directly imported into the AltiMap professional surface topography evaluator program with which the evaluation per standard roughness parameters can be conducted. A great advantage of the worked-out method is that the theoretical and real roughness data can be evaluated on the same basis, thus these can be more easily compared.

3. Results of Investigations

Theoretical values of roughness which were calculated by the model and the real roughness data which were measured on surfaces machined by a single circular insert are summarized in Table 2. The investigated feed domain was varied between a_p/f_z ratio of $4.76 \div 0.52$ with a constant depth of cut ($a_p = 1$ mm). Of course, not only the roughness characteristics introduced in the table can be defined, but also all the standard roughness values; only a part of the measured values are presented here.

Table 2
Roughness parameters for different feed values in fly-cutting

f_z	2D roughness, [µm]		3D roughness, [µm]	
	Theo.	Meas.	Theo.	Meas.
f_{z1}	Ra = 0.17 Rz = 0.69 Rt = 0.69	Ra = 0.11 Rz = 0.66 Rt = 1.18	Sa = 0.18 Sz = 0.69	Sa = 1.07 Sz = 8.5
f_{z2}	Ra = 1.63 Rz = 6.4 Rt = 6.4	Ra = 2 Rz = 9.23 Rt = 9.86	Sa = 1.62 Sz = 6.4	Sa = 1.98 Sz = 11.85
f_{z3}	Ra = 4.49 Rz = 17.58 Rt = 17.58	Ra = 4.95 Rz = 19.5 Rt = 20.45	Sa = 4.51 Sz = 17.58	Sa = 4.92 Sz = 25.79
f_{z4}	Ra = 8.71 Rz = 34.3 Rt = 34.3	Ra = 8.83 Rz = 38.32 Rt = 38.67	Sa = 8.96 Sz = 34.3	Sa = 8.85 Sz = 41.76
f_{z5}	Ra = 14.85 Rz = 57.81 Rt = 57.81	Ra = 14.4 Rz = 59.57 Rt = 61.85	Sa = 14.82 Sz = 57.81	Sa = 13.54 Sz = 69.8

Two-dimensional roughness profiles for three different feed values in fly-cutting are introduced in Figs. 2–4, while the three-dimensional roughness surfaces are shown in Fig. 5.

As usually more than one inset is used simultaneously in milling heads, the effect of the application of two inserts on the surface was also analyzed for a case when the inserts have setting errors (in axial and radial directions) with respect to one another.

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 those were not considered in the calculations.
The consideration of setting errors is important because the dynamical conditions of cutting are changing in this case, and the tool edge marks are shifted to each other with the value of the setting error.
Theoretical and real values of the characteristic topography of surfaces machined by two circular inserts are summarized in Table 3.

Table 3
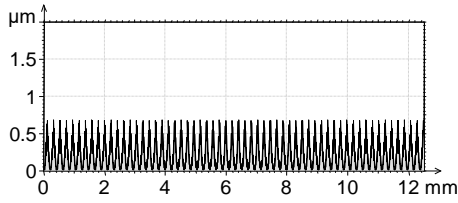Roughness parameters for different feed values in milling with two inserts

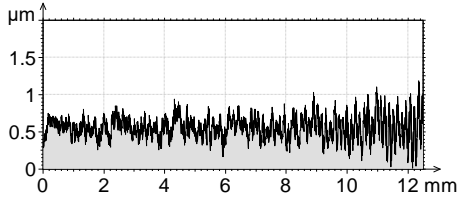| f_z,	2D roughness, [µm]		3D roughness, [µm]	
	Theo.	Meas.	Theo.	Meas.
f_{z1}	Ra = 0.7 Rz = 2.76 Rt = 2.76	Ra = 1.13 Rz = 6.09 Rt = 7.14	Sa = 0.7 Sz = 2.76	Sa = 1.23 Sz = 9.7
f_{z2}	Ra = 6.57 Rz = 25.64 Rt = 25.64	Ra = 6.48 Rz = 26.76 Rt = 27.86	Sa = 6.56 Sz = 25.64	Sa = 6.19 Sz = 31.39
f_{z3}	Ra = 18 Rz = 65.11 Rt = 65.11	Ra = 17.67 Rz = 73.87 Rt = 73.89	Sa = 17.8 Sz = 65.11	Sa = 17.77 Sz = 84.62
f_{z4}	Ra = 24.6 Rz = 74.53 Rt = 74.53	Ra = 22.88 Rz = 79.41 Rt = 84.84	Sa = 23.72 Sz = 74.53	Sa = 24.72 Sz = 95.97
f_{z5}	Ra = 28.5 Rz = 94.92 Rt = 94.92	Ra = 27.83 Rz = 98.17 Rt = 102.6	Sa = 29.37 Sz = 94.92	Sa = 26.57 Sz = 102.3

4. Evaluation of Experimental Results

The theoretical and real values are shown in Fig. 2. ÷ Fig 4 for milling with one circular insert.
It can be seen from the experimental results that increasing the feed results in the significant, exponential increase of the roughness.
Analysis of the values determined from the theoretical profile shows that the values closely follow the changing of the feed. Moreover, it can be seen that both profiles, as well as roughness values, show good agreement between theoretical and real values of roughness.
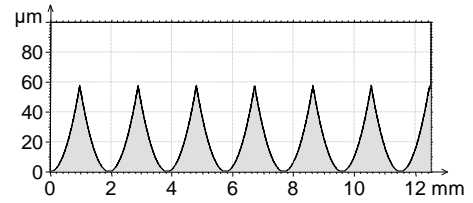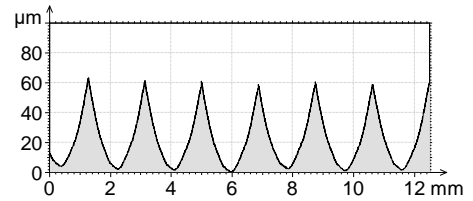
a) theoretical

b) measured

Fig. 2

Theoretical and measured 2D profile diagrams of surfaces milled with one circular insert for f_{z1}
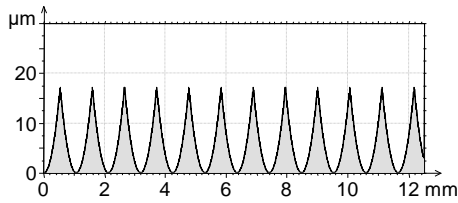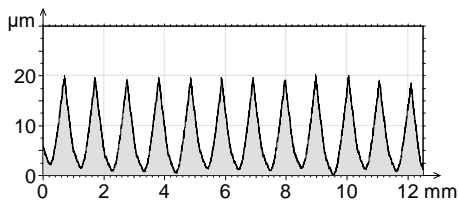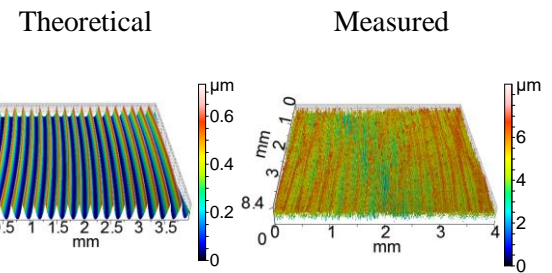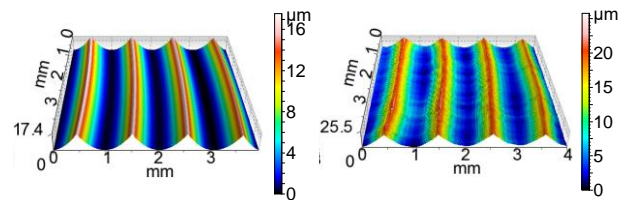

a) theoretical

b) measured

Fig. 3

Theoretical and measured 2D profile diagrams of surfaces milled with one circular insert for f_{z3}

With the analysis of profiles, it can be clearly seen that the agreement between theoretical and real profile becomes better with increasing feed. This can be attributed to the fact that effects of other chip removal characteristics are proportionally more significant at low feeds compared to the other geometrical characteristics that were used to create the CAD model.
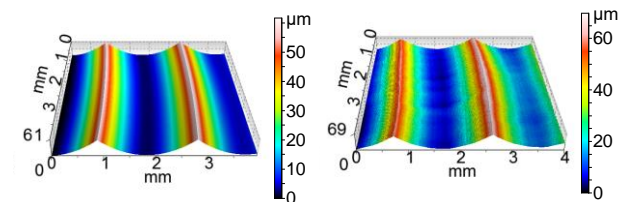
It should be noted here, that not all of the simulated theoretical and measured real profiles are showed here but only some relevant examples from them.

a) theoretical

b) measured

Fig. 4

Theoretical and measured 2D profile diagrams of surfaces milled with one circular insert for f_{z5}

Theoretical   Measured

a) f_{z1}

b) f_{z3}

c) f_{z5}

Fig. 5

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

While the inserts always have some extent of setting errors, it is an important advantage of the model that it can take these deviations into consideration. The theoretical and measured profiles

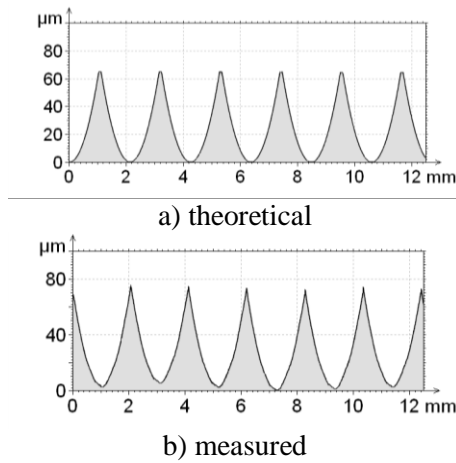for cutting with two circular inserts are shown in Figs. 6–8.

a) theoretical

b) measured

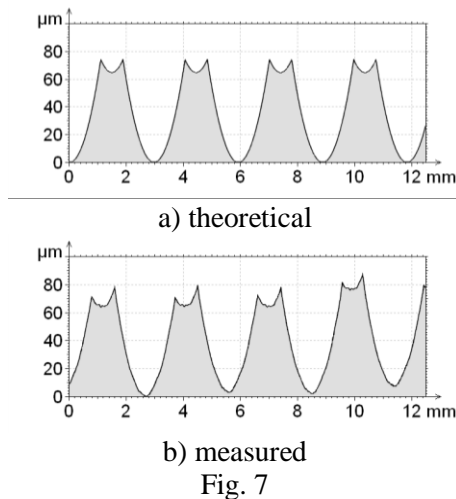Fig. 6
Theoretical and measured 2D profile diagrams of surfaces milled with two circular insert for f_{z3}

a) theoretical

b) measured

Fig. 7
Theoretical and measured 2D profile diagrams of surfaces milled with two circular insert for fz4
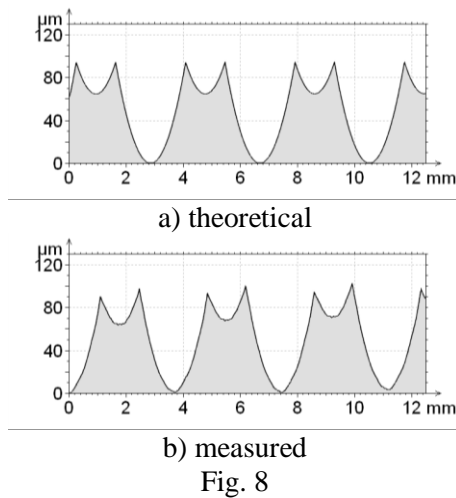

a) theoretical

b) measured

Fig. 8
Theoretical and measured 2D profile diagrams of surfaces milled with two circular insert for fz5

As was mentioned before, 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 edge values. The reason for this is that the insert which 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. Practically, the chip removal was performed by this insert only with feed per tooth values set at $f_z = 1.48$ and 1.98 mm. The developed CAD model was extended to be able to determine theoretical roughness values of resulting topographies in such cases. The simulated theoretical and the measured three-dimensional surfaces are summarized in Fig. 9 when cutting with two circular inserts with setting errors.

Theoretical　　　　**Measured**

a) f_{z3}
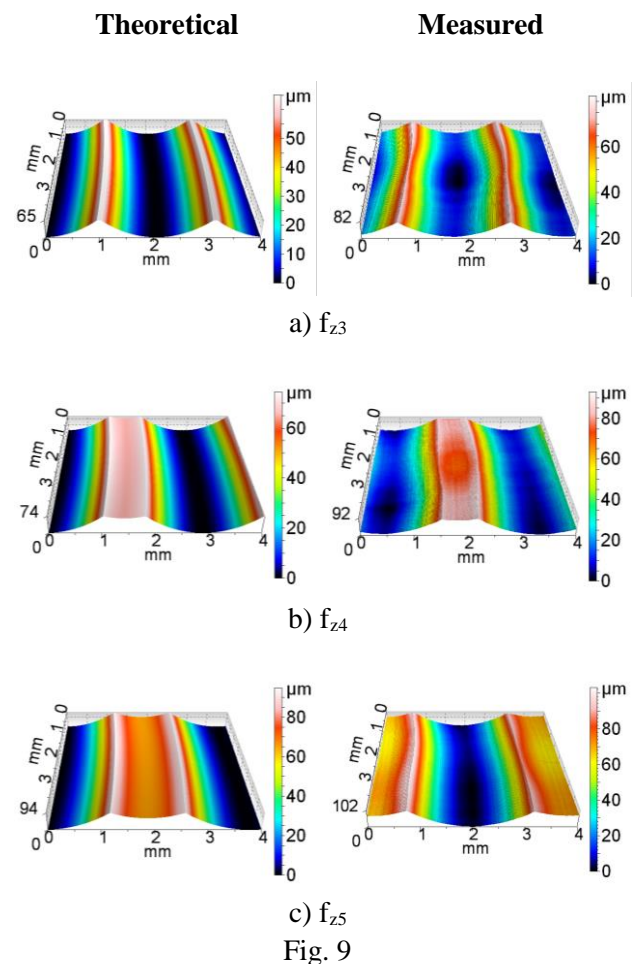

b) f_{z4}

c) f_{z5}

Fig. 9
Theoretical and measured 3D surface diagrams of surfaces milled with two circular inserts

Finally, theoretical and real roughness values are compared, as well as their changing character as a function of the feed. It can be concluded that the theoretical roughness values determined by the

model show good agreement with the measured values both in their character of change and in the values themselves. It can be stated from Figs. 10 and 11 that the accuracy of the values by the model is sufficient to predict the actual roughness.
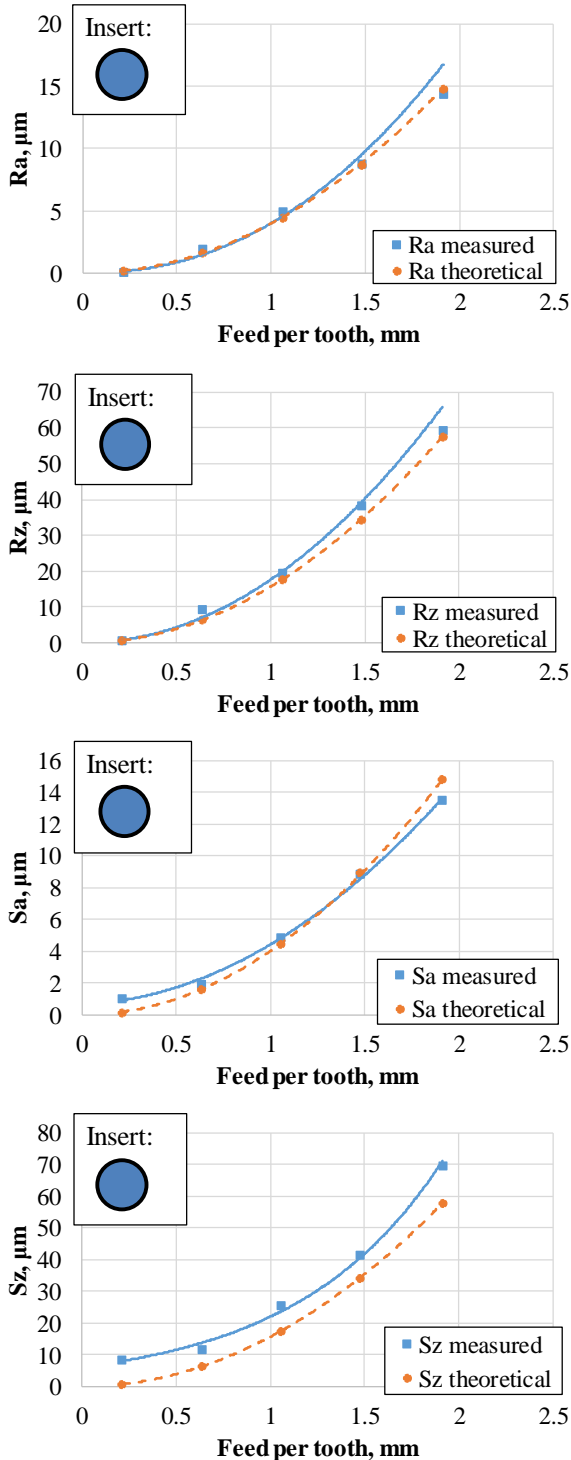
The relation between theoretical and real surface roughness characteristics can be seen from the comparison graphs in Figs. 10 and 11.

Fig. 10
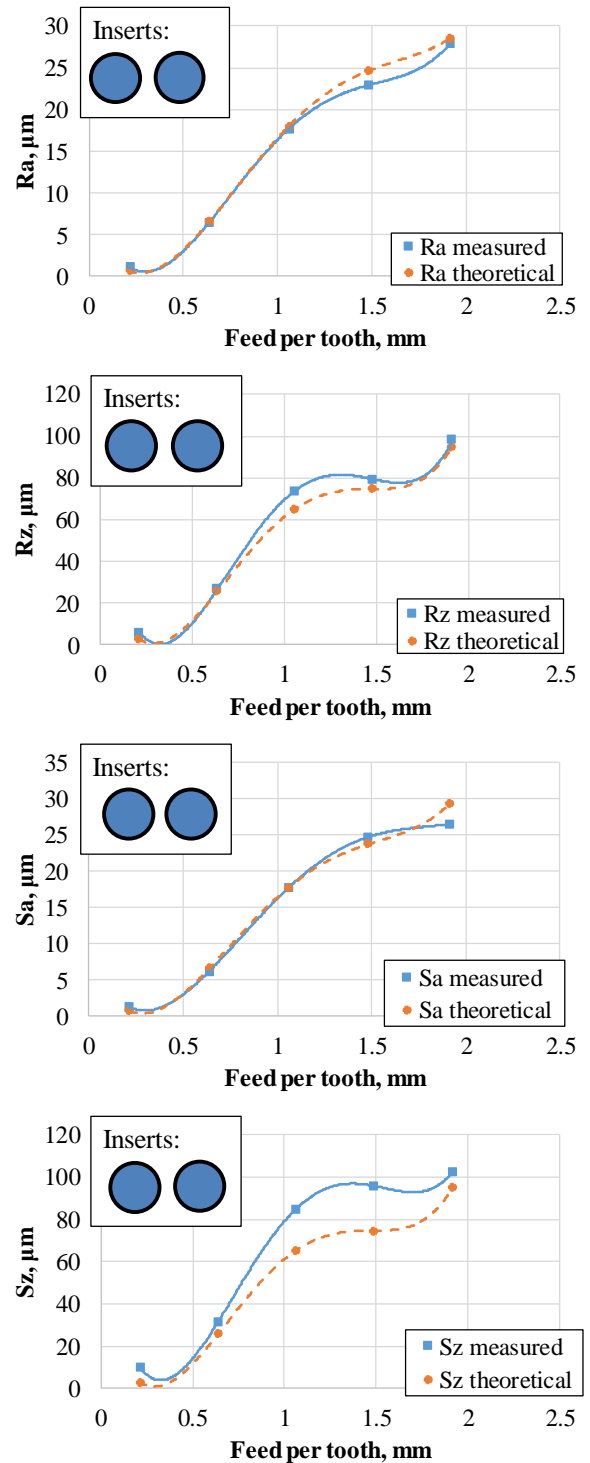Changing of roughness characteristics of surfaces milled by one circular insert as a function of feed

Fig. 11
Changing of roughness characteristics of surfaces milled by two circular inserts as a function of feed

The good agreement also applies to the two inserts that have setting errors to each other (Fig. 11).

5 Discussion

The automation of production, the spreading of flexible manufacturing systems and the proliferation of computer technology allows technological processes and their products to be planned with ever growing accuracy. The accurate planning of the topography of generated surfaces of parts facilitates even better compliance with functional requirements of surfaces in the final machining of parts, which can significantly extend their lifespan. Analysis of the changing of micro-geometrical properties and surface roughness values of face milled surface topographies as a function of technological data has long been an important direction of research.

Part production in which the allowance is essentially removed in one cut is becoming more common; therefore, choosing the feed value is becoming more important. Increasing the feed increases the machining productivity, but at the same time the roughness also increases. Thus, the research is aimed at using only one cut on a part with increased feed, thus achieving higher productivity while keeping the increase in roughness under control (it must be in accordance with prescriptions for the surface). This is extremely important in finishing operations where the formation of surfaces providing functional properties is done. The simultaneous effort to produce the blanks with as minimal an allowance as possible and to remove the allowance in one cut makes it even more important to analyze the effects of the feed.

6. Conclusions

The effect of changing feed on the roughness characteristics of face-milled surfaces was introduced in the paper. In addition to the data obtained during cutting experiments their theoretical values under identical conditions were also defined. A CAD model was applied for the latter. Both the theoretical 2D and 2D roughness profiles exhibit good correlation with cut surface profiles calculated with the introduced method, which was elaborated for the determination of theoretical values. The model is suitable for the determination of 2D and 3D theoretical values of roughness parameters. In case of a nearly ten-fold change in a_p/f_z values, the theoretical roughness values and their change followed the real roughness values with good correlation. In addition, experiments with two inserts introduced to show the effect of the setting error confirmed the applicability of the method. The overall conclusion is that the method is well suited for the estimation of expected roughness values.

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