

A Method for the Determination of Theoretical Roughness in Face Milling Considering the Run-Out of the Inserts

Csaba FELHO^{1,a*}, Janos KUNDRAK^{1,b}

¹Institute of Manufacturing Science, University of Miskolc, Hungary

^acsaba.felho@uni-miskolc.hu, ^bjanos.kundrak@uni-miskolc.hu

Keywords: Surface Roughness, Face Milling; CAD Modelling

Abstract. A method is introduced for determining theoretical values of roughness characteristics of surfaces generated by tools having a defined edge geometry. The method is based on the CAD modelling of the theoretical cut surface, and can be used to model practically any complex tool geometry. In application to rotating tools (e.g. face milling), besides the variety of tool designs, the setting accuracy was also taken into consideration during the determination of theoretical values due to the simultaneous cutting of more than one edge. It will be demonstrated that in addition to the determination of 2D roughness parameters, the method is suitable to determine the 3D roughness parameters as the surface topography can be more accurately described with these characteristics. Experimental data is shown to validate of the extended modelling and calculation method.

Introduction

Increasing attention is being given to increasing the efficiency of face milling processes [1]. As the applied feed rate value substantially influences the operation time at cutting processes, one solution is the application of as high a feed rate as possible. With the increasing feed (and if the depth of cut remains constant), the chip cross section and therefore the cutting forces and the required power will dramatically increase, thus another trend is to decrease the removed material thickness simultaneously (axial depth of cut). The objective is to obtain surface quality meeting the specifications by machining of the raw part in as few cuts as possible or even in one cut. Researchers have been intensively dealing with the modelling of the roughness of machined surfaces as well as with the determination of the expected roughness of surfaces machined with the planned parameters. Often different modelling procedures are utilized [2].

A modelling method is introduced in [3] that is based on a geometrical analysis of the recreation of the tool trail left on the machined surface. During the modelling, particular attention was paid to tool setting errors (axial and radial). Not only the theoretical values were determined with the developed procedure, but also two-dimensional theoretical roughness profiles were produced. A grey-fuzzy modelling method was applied in [4] for determination of the optimal process parameters for end milling of an aluminium alloy. Investigated process parameters were Centre Line Average Roughness (Ra), Root Mean Square Roughness (Rq) and Material Removal Rate (MRR). A hybrid approach is presented for the modelling of surface roughness in slot milling in [5], where the analytical calculation of the specific energy consumption (SCEC) and empirical relations between the SCEC and surface roughness are combined in one model. It was found that a direct connection exists between the specific energy consumption (the cutting power required to remove 1 mm³ 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 analysed experimentally in [6] by using ANOVA in face milling of wrought cast steel (WCB grade B) workpieces. FEM modelling was applied in [7] in order to investigate the effects of feed on surface roughness (Ra) and components of cutting force (F_c , F_f) in face milling of a titanium alloy. Modelling and experiments showed that the prediction of the expected roughness can be done on the basis of an equation with the feed directional force component obtained by FEM modelling.

The 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 [8] using the response surface methodology (RSM) in hard milling of 4340 alloy steel with only minimal lubricant. It was found that increasing cutting speed will decrease surface errors and increasing any investigated parameter will increase micro-hardness and white layer thickness. Theoretical description of the surface pattern which evolves in face milling is performed in [9], where both mathematical calculations (MATLAB) and CAD simulations were utilized to investigate effects of various workpiece and tool designs and positions, feed and the angle between the milling axis and the machined surface on the quality (roughness) of the machined surface. The effects of the up- and down-milling method and the changing of technological parameters on surface roughness in milling thin-walled workpieces were investigated by an analytical modelling method [10], while RSM was utilized in [11] to analyse effects of 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 cutting parameters and the axial and radial setting errors were considered in the surface prediction method presented in [12], but also dynamical phenomena resulting from the cutting tool deflections in end milling. In [13] optimal cutting parameters were determined, resulting in minimal roughness characteristics in 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. Experiments for training and for validation were performed by machining of Ti-6Al-4V ELI alloys. An artificial neural network was designed and utilized in [14] to predict surface roughness when drilling nickel based super alloy UDIMET 720. Selected parameters were used to design a suitable algorithm for control and monitoring the drilling process with respect to surface roughness. The influence of the tool coating on surface quality, especially on surface roughness (R_z), was investigated in [15]. Both coated and uncoated tools were used in the tests, and the resulting surface was measured and compared, presenting a clearly experimental method for surface roughness modelling. A statistical design for experiments was performed in [16] to investigate the effect of selected cutting parameters (helix angle, cutting speed) and a cutting fluid on the surface roughness of AlMgSi1 aluminium alloy machined by end milling. The helix angle was found to be the most significant parameter for surface roughness.

The topic of the article is the investigation of the effect of increasing the feed and thus the changing of the chip cross-section on the roughness of the machined surface in face milling. The application area of the previously developed model [17] was extended to an increased feed domain. It is well known that the increased feed causes deterioration of the machined surface roughness [18]. However, in the case of constant chip cross section, through the changed cutting ratio (a_p/f_z ratio) both the main cutting force F_f , the feed force F_f and the passive force F_p decrease due to the decreasing of the chip width h , and thus the required cutting power P_c . This can be advantageous for the quality of the machined surface [19].

Here, investigations are carried out by a method developed by the authors [20] that is able to determine the values of theoretical surface roughness indexes in face milling. The basis of the method is the CAD modelling of the machined surface; its surface points (x , y and z coordinates) are transferred into a professional surface topography analysis software with an interface program, where the evaluation of standard two- and three-dimensional roughness parameters can be performed. The same surface topography measurement and analysis system is used for the validation of data obtained by theoretical modelling through roughness profiles and values measured on surfaces machined in cutting tests.

Investigation method description

Several methods are known for the description of the surface topography generated by cutting tools having defined edge geometry. Usually trigonometric equations are used to describe the cutting edges, and then the intersection points of the original and shifted-by-the-feed profiles are calculated, thus determining the points of the theoretical roughness profile. Kundrak has developed a method [18] in which the cutting tool is placed in an x-y coordinate system, where the intersection point of the major and minor edges (the tool tip point) is at the origin. Thus, the edge sections of the cutting tool become deductible by simple equations (by lines and arcs). Simple calculation of theoretical roughness characteristics also becomes possible. However, this method can be applied only for single point cutting tools, primarily in turning. In other machining methods, e.g. in face milling, the analytical calculation of theoretical roughness has difficulties, since the surface topography created by the rotating tool can be quite complex [17] if analysed not only in the milling head centreline.

The method introduced in this paper allows a more comprehensive analysis compared to the previously used techniques. A great advantage of it is that it allows the recording of two-dimensional (2D) profiles in arbitrary measurement positions and directions. A further innovation of the method is that it can generate three-dimensional (3D) surfaces, so it is also suitable for the determination of 3D theoretical roughness indexes. The applied principle can be used for practically any cutting method, as it allows the analysis of the complex surface topography generated by the relative movements of the cutting tool and the workpiece. The following describes the process of model creation as well as the structure and operation of the developed interface program.

The modelling process and the evaluation method

The first step in application of the method is to prepare a 3D theoretical model of the cut surface. This can be accomplished in any parametric CAD system; here the Siemens NX program has been chosen. The raw part was modelled as a simple prism (50 x 50 x 100 mm). During the modelling of the tool, the shape of the cutting insert was drawn in the tool reference plane. This was followed by the description of the cycloid trajectory of the pitch point of the insert that results from the rotating motion of the tool and the linear feeding motion. The insert shape was guided along this trajectory and thus the swept volume of the insert was obtained. The theoretical model of the machined surface was achieved by cutting this volume from the workpiece model and by the multiplication of this feature with the shift value according to the feed per tooth. All characteristics were defined as user parameters during the modelling, thus the developed model provides great flexibility to quickly define the desired tool geometrical and technological parameters.

In the next step, the transferring of the points of the previously generated surface was accomplished to the surface topography analysis software with a suitably developed interface program containing four core modules: an integration module into the user interface of the CAD system, a module that queries the points of the model points, a module for the handling and transformation of the obtained points, and finally a SURF file handling module for the creation of the output file.

The evaluation according to the requested 2D or 3D surface roughness characteristics and the visual presentation of the roughness profiles or surfaces can be performed by reading the resulting surface points (x, z or x, y, z coordinates for profiles or for surfaces, respectively) into the AltiMap commercial surface roughness evaluation software. One big advantage of the method is that the determination of both theoretical and real roughness characteristics is performed on the same basis (in the same evaluation software) and therefore their comparison is exact. Another major advantage is the ease of introducing more factors into the model. In the present research, only one insert was applied in the milling head both in theoretical investigations and in cutting experiments; however, the axial and radial run-out values between the respective cutting edges can be considered in the model when using more inserts.

Theoretical profiles obtained by modelling are shown in Fig. 1. A single round insert was used for the simulation ($iC = 12$ mm), and applied geometrical and technological parameters were identical to the experimental values (see Table 1). Fig. 2 shows the theoretical surfaces obtained by application of the CAD modelling method.

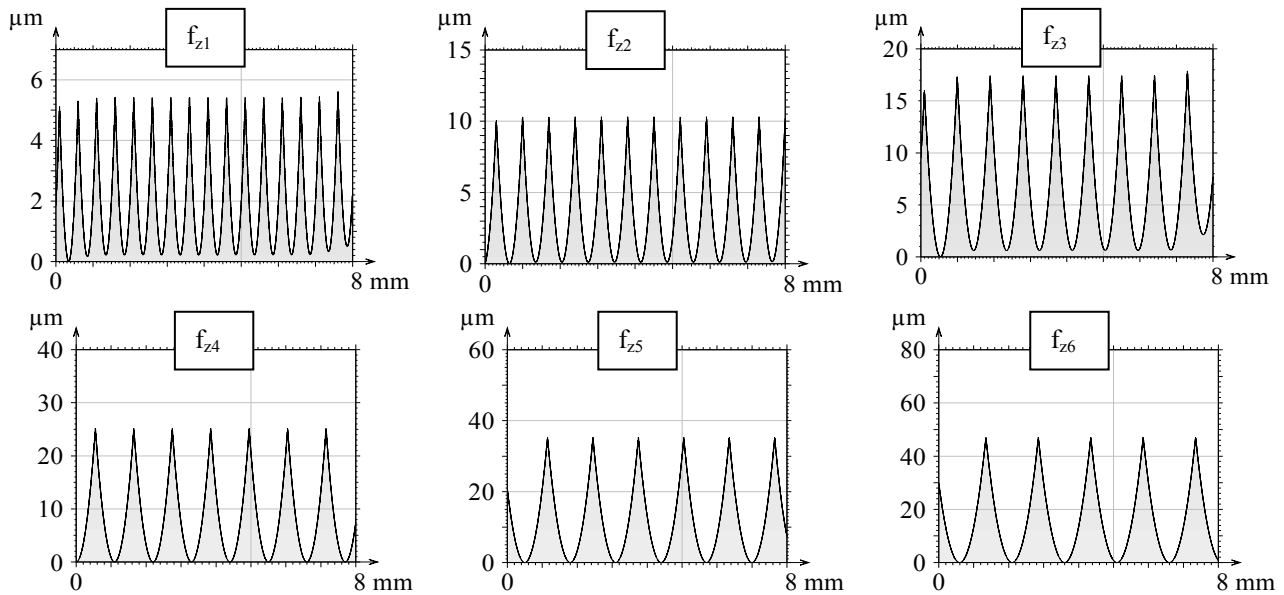


Fig. 1. The obtained theoretical profiles

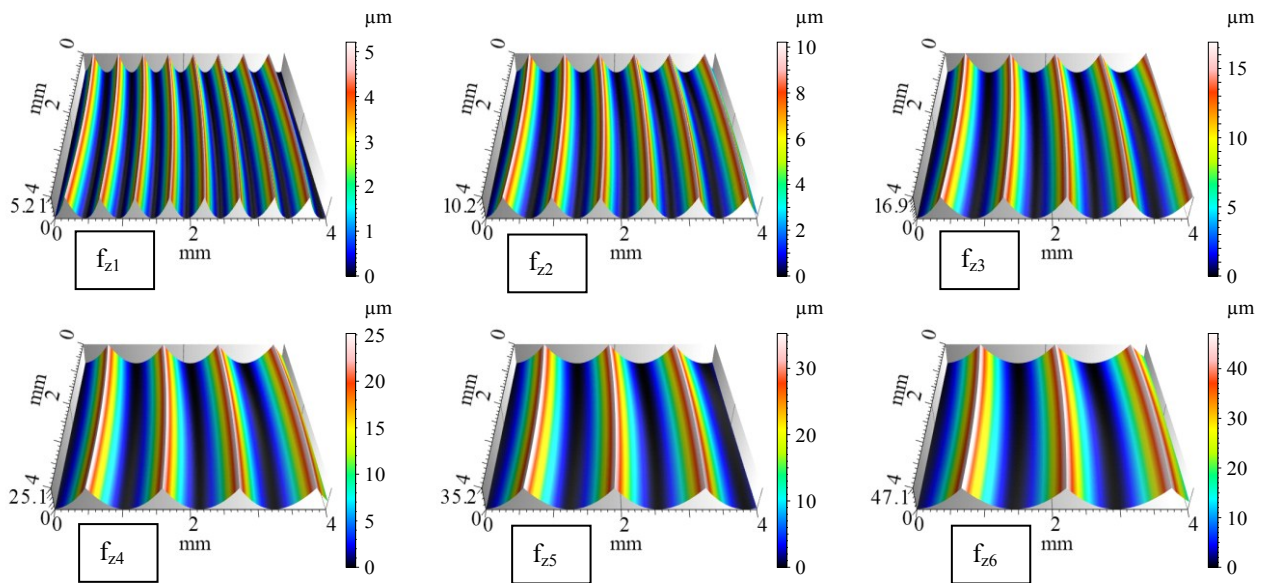


Fig. 2. The modelled three-dimensional surfaces

Experiments for the validation of the introduced method

Cutting experiments were conducted in order to validate the applicability of the previously introduced modelling procedure and calculation method.

Experimental conditions: The applied machine tool was a Perfect Jet MCV-M8 CNC vertical machining centre. The cutting tool was a Sandvik Coromant R200-068Q27-12L face milling head with an RCKT1204M0-PM 4230 cutting insert (round insert). Only one cutting insert was placed into the milling head during the experiments (fly-cutting). The machined test samples were 50 x 50 x 100 mm prisms from normalized C45 steel material, a plain carbon steel commonly used for mechanical engineering and automotive components. The parameters applied are given in Table 1.

Table 1. The applied technological data

	1	2	3	4	5	6
f_z [mm]	$f_{z1} = 0.5$	$f_{z2} = 0.7$	$f_{z3} = 0.9$	$f_{z4} = 1.1$	$f_{z5} = 1.3$	$f_{z6} = 1.5$
n [rev/min]	950					
a_p [mm]	0.9					
a_e [mm]	50					

Results: The measurement of the surface roughness was conducted on the AltiSurf 520 surface analysis equipment, with the application of a CL2 confocal chromatic probe. For the evaluation of data, AltiMap software was utilized. The 2D profiles are introduced (Fig. 3) that were recorded in the centreline of the milling head along the feed direction, according to ISO 4288:1998 and ISO 3274:1998 standards. The real 3D surfaces, which were measured and evaluated according to the ISO 25178-2:2012 standards, are introduced in Fig. 4.

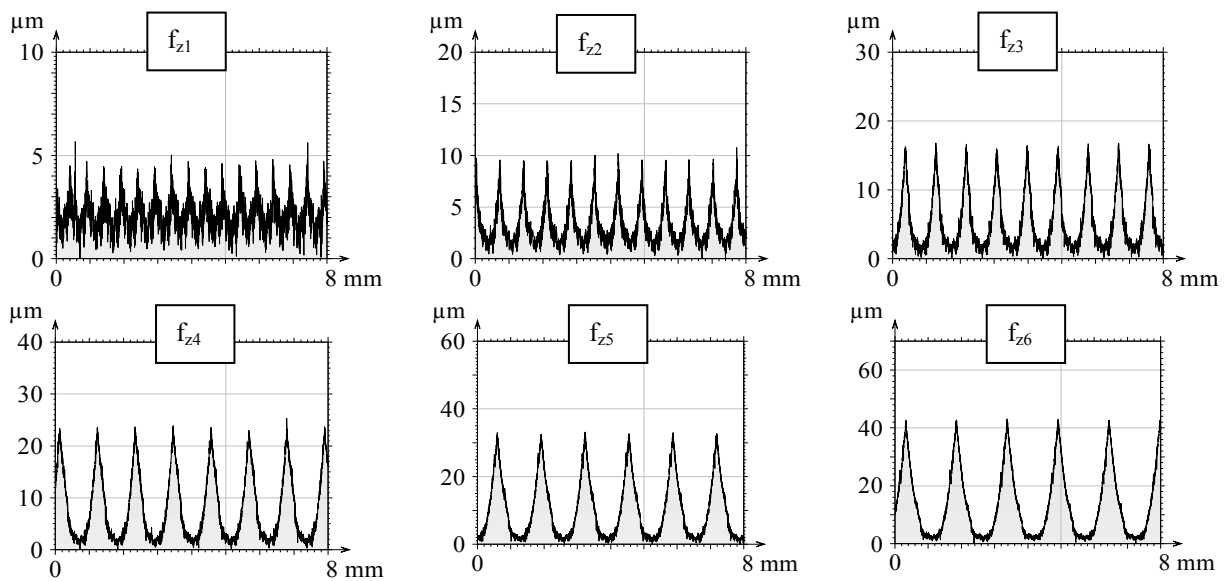


Fig. 3. The measured profiles

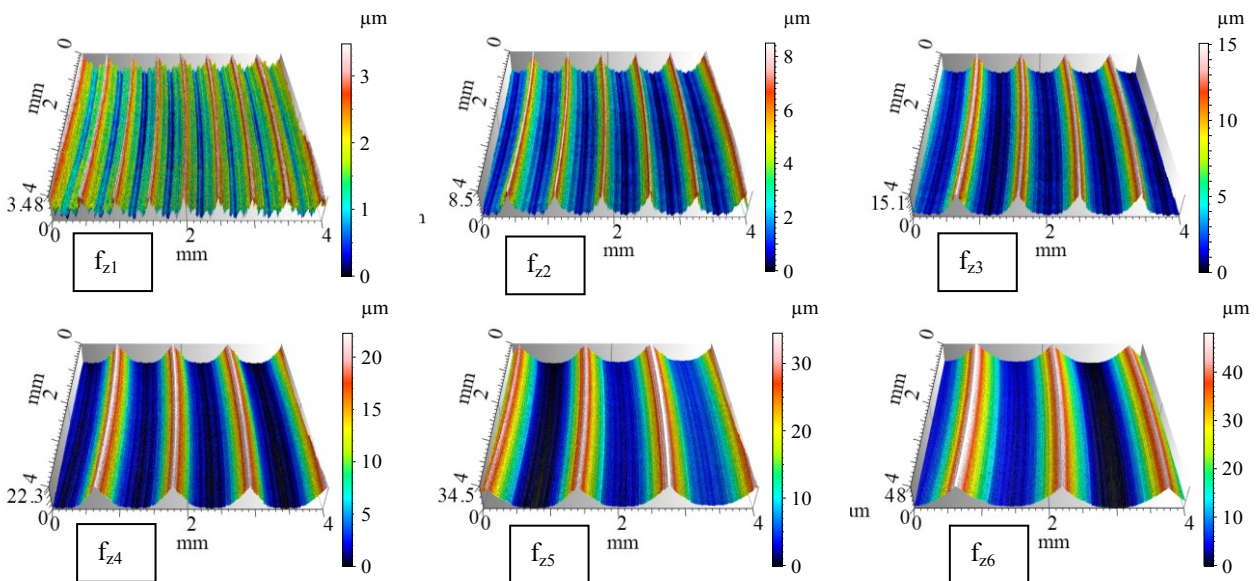


Fig. 4. The measured three-dimensional surfaces

Evaluation of results

As can be seen from the figures, the profiles (Figs. 1 and 3) and surfaces (Figs. 2 and 4) are in good agreement. The higher the value of the feed per tooth, the better the correspondence. A possible explanation could be that in the region of lower feed values (particularly for $f_z < 0.5$ mm) the side effects of chip removal (such as vibrations in the milling cutter, tearing of the workpiece material during chip removal, built-up edge, defects in the homogeneity of the workpiece material, undeformed chip thickness and tool wear), the rounding radius and the roughness of the cutting edge have a greater influence ratio on the character of the surface topography. The closer the high-feed milling range becomes ($f_z > 0.5$ mm), the more convincing the goodness of the model is.

Numerical values of theoretical and real roughness parameters are introduced in Figs. 5 and 6. These figures show a quadratic increase in the roughness values for both examined 2D (Ra and Rz) and 3D (Sa and Sz) characteristics, which corresponds to data in the literature. However, it should be noted that slightly greater roughness values were determined by the model compared to the data obtained on measured surfaces, particularly for the Ra and Sa parameters. This can be attributed to the stronger dominance of plastic deformation in case of the round insert with relatively large radius (compared to the roughness), where the cutting effect insufficiently prevails at the tool edge, so that the roughness profile is distorted from the theoretical one.

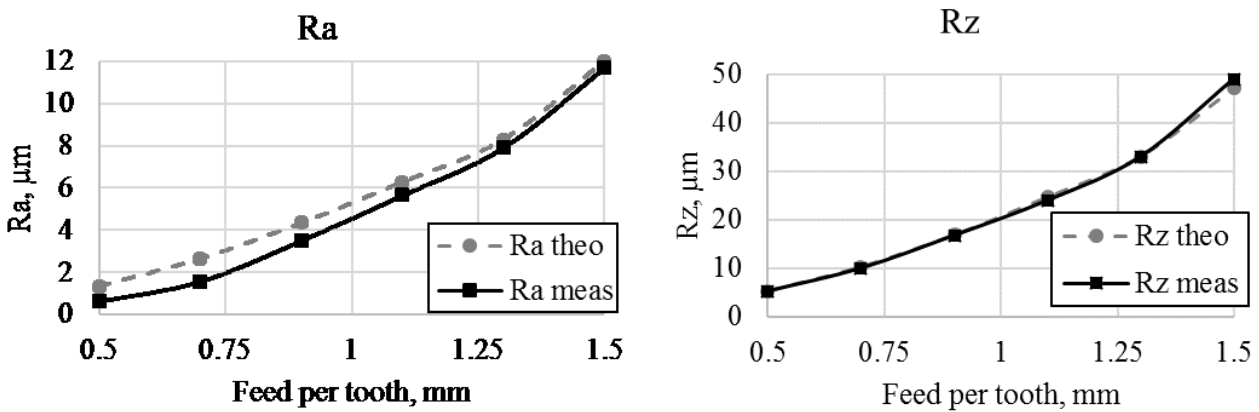


Fig. 5. Comparison of two-dimensional roughness indexes

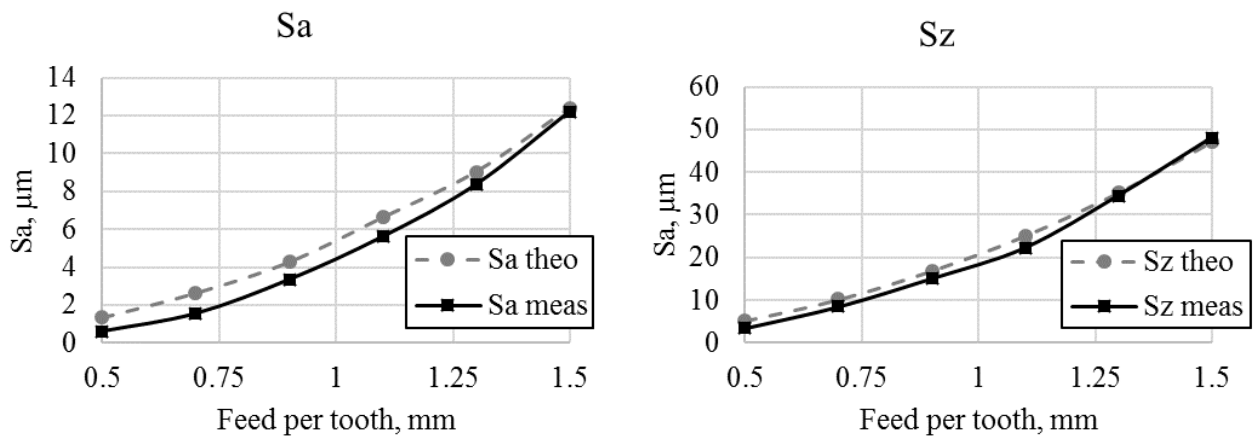


Fig. 6. Comparison of three-dimensional roughness indexes

Fig. 7 shows the regression line indicating the correlation between the modeled and measured values of certain roughness characteristics. It can be seen that the best match is in the Rz and Sz parameters.

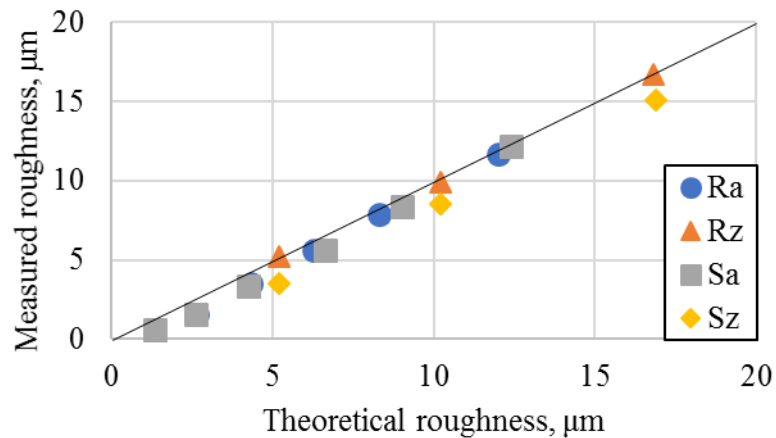


Fig. 7. Correlation between theoretical and real roughness indexes

Conclusions

The method described in the paper provides a good opportunity for the modelling of the topography of machined surface in order to determine theoretical values of surface roughness and to estimate the expected roughness of surfaces machined under given conditions in face milling. Based on the performed experiments, it was found that the accuracy of the approximation improves with increasing feed; therefore, the application of the procedure is particularly effective in high-feed milling. Moreover, the method can be further developed with minor modifications (by modelling the appropriate process kinematics) to investigate other milling types (e.g. for 3D milling of rounded surfaces as it was introduced in [21]) or even for other machining methods as well.

Acknowledgement

The authors greatly appreciate the support of the National Research, Development and Innovation Office – NKFIH (No. of Agreement: OTKA K 116876).

This study was carried out as part of the EFOP-3.6.1-16-00011 “Younger and Renewing University – Innovative Knowledge City – institutional development of the University of Miskolc aiming at intelligent specialization” project implemented in the framework of the Szechenyi 2020 program. The realization of this project is supported by the European Union, co-financed by the European Social Fund.

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