

Surface roughness prediction in face milling by special tools

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Abstract. The ability to plan the surface roughness in case of machining by rotational tools is introduced in the paper by the help of a formerly developed calculation method. This method utilizes the theoretical surface roughness indexes which were calculated in advance for the prediction of the expected surface roughness parameters. An experimental milling head is considered for the theoretical and experimental investigations, which can contain different insert geometries. The paper describes two distinct cases: in the first case, the face milling is performed by two identical cutting inserts, while in the second one, two different insert are applied simultaneously. Results of the carried-out experiments are also presented for the validation of the theoretical calculations.

Introduction

Topography planning ability of generated surfaces of parts is more and more important nowadays, whereas if the parts can be machined in such a manner which corresponds to the working requirements then their lifespan can be significantly improved. Its recognition is indicated in the fact that the investigation of surface roughness characteristics of machined surfaces and the impact of the processes and cutting data, the tool edge geometry etc. on the roughness and the presentation of the results are published in scientific works and different publications since a long while (Table 1 [1]).

The number of research groups and the investigation methods have been expanded from that time. Even if only the Central-European region is considered, several works have been appeared in connection with the investigation and modelling of surface roughness at different machining processes, among which a few will be described.

The contribution by Beno et al. [2] introduces practical methodology of roughness measurement when turning by tool inserts with variable tool face. Measuring array consists of combination of four feeds per revolution and three depth of cut while use of two cutting speeds denotes such methodology as 4–3–2 roughness measurement. Relationships among surface roughness parameters show how roughness ranges measuring area throughout. Processing and evaluation of data give well founded information to choice proper tool insert as practical contribution related to machining plans.

Another article from the same research team (Vrabel et al [3]) deals with design of artificial neural network (ANN) for prediction of the surface roughness as one of the important indicators of machined surface quality. Back propagation neural network was trained and tested for prediction of the machined surface roughness. Cutting conditions, selected monitoring indices and tool wear parameter were given as inputs to the ANN. Test sample was nickel based super alloy Udimet 720, which is used as material for highly stressed jet engine components. Experimental data collected from tests were used as input into ANN to identify the sensitivity among cutting conditions, monitoring indices and progressive tool wear and machined surface roughness.

The cutting of high hardness composite materials such as sintered carbides based on the cobalt is a challenge from a technological point of view. Zebala et al. [4] presents the influence of cutting

data (v_c , f , a_p) and cobalt content in a work piece (10, 15, and 25 wt%) on the turning process of WC-Co with polycrystalline diamond (PCD) tool. This study focuses on the main component of cutting force F_c and surface roughness, described by the roughness parameter R_a . The research plan, based on the Taguchi method, and variance analysis ANOVA were applied. Two types of experimental model, which describes turning process of sintered carbides based on the power function for three variables and polynomial functions as a modified method of the response surface methodology (RSM), were also presented.

Table 1. Some research groups and modelling techniques in connection with surface roughness modelling according to [1]

Modelling procedures and techniques	Some currently active research groups
Analytical models or computer algorithms	Grzesik; Lin and Chang; Baek et al.; Chen et al.; Ehmann and Hong; Kim and Chu; Li and Li, Biermann and Surmann, Kundrak
Based on experiments	Abouelatta and Madl; Ghani and Choudhury; Sai and Bouzid; Grzesik, Gokkaya and Nalbant, Dhar et al.; Munoz-Escalona and Cassier; Diniz and Filho; Correia and Davim
Based on designed experiments	Davim; Feng and Wang; Kopac and Bahor; Vivancos et al.; Arbizu and Perez; Sahin and Motorcu; Thiele and Melkote
Based on artificial intelligence (AI)	Colak et al.; Ozel and Karpat; Benardos and Vosniakos; Zain et al.; Raj and Namboothiri; Lo; Abburi and Dixit

The adequate knowledge in the areas of high precision metrology is of extreme importance in industry and production to achieve necessary and required efficiency, accuracy and quality. Fulfillment of the successful application of modern machining in series manufacturing depends to a great extent from the (geometrical) workpiece tolerances of any kind (roughness, form, positional, dimensional) which are prescribed for the production and the fulfillment of these tolerances and therefore for the economy of production altogether. There are studies presenting a comprehensive analysis of the workpiece geometry and surface for further development [5, 6].

In the case of ideal circumstances the accuracy and surface roughness of the machined holes are surprisingly favourable. A study by Palásti-Kovács et al. [7] describes the experimental research of the force effects and the quality of the bore (accuracy, concentricity, surface roughness), developing during the drilling operation of the wide range of material groups.

In practice it is not enough to reach a sufficient cutting condition besides the right combination of the construction-geometry-coating triple. The lifetime of parts and their functional behavior and reliability depend, besides shape and bore accuracy, on the deviation of the microgeometry of the machined surface (waviness (W) and roughness (R)): on surface quality in a broader sense. It is not enough to deal with the roughness (R) profile, but the unfiltered (P) profile should rather be focused on, which is the topic of a paper by Szaloki [8].

In case of 3D surface milling, the main component of the surface roughness is the cusp height, which depends on the tool geometry, the step over parameter and the position of the surface. Based on Mikó and Beno [9] the effect of the changing working diameter and cutting speed on the surface roughness can be compensated by the changing number of revolution, which ensures constant cutting speed. A paper by Varga et al. [10] briefly describes the development of surface characterization to its current 3D capability in the drilling process. It shows how selected parameters can assist with drill process analysis and how this can be supported through the introduction of the planned new ISO International Standard for 3D Surface characterization. The paper is supported by a sample-drilling test to demonstrate the power of the proposed analysis.

With the introduction of these few works that may be perceived, that the researches are very manifolds. In the current article, a method will be shown for the characterisation of surface

topography and for the determination of roughness parameters at cutting with rotary tools with inserts having identical and varied edge geometry.

Method for description of theoretical surface topography at rotating tools

In what follows the worked-out method will be described for the determination of theoretical parameters at machining by rotary tools and its application will be introduced. The particular procedure which will be introduced in the paper is a face milling performed by a specially designed tool. The motivation for this came from that researchers at the Otto-von-Guericke University in Magdeburg, Institute of Manufacturing Technology and Quality Management (IFQ) have developed such a milling tool construction, which is suitable to place inserts with different edge geometries in a specially designed milling head simultaneously, in order to obtain some chip removal optimum criterion [11]. Several experiments were conducted with this tool since then, and they have found, that there is a great potential to decrease the cutting forces and vibrations with the chip form optimization [12].

The further development possibility of these researches can be the optimization on the basis of the topography of the cut surface. Therefore the goal of the present research is the theoretical description of the topographies generated by cutting inserts having different geometries, and their comparison with real roughness data measured during cutting experiments. The expected roughness of cut surfaces can be forecasted by giving the relations between theoretical and real roughness data for the particular material/tool matching. Theoretical values of surface roughness can be calculated with the knowledge of the tool-geometrical characteristics and the technological parameters which affects the surface roughness mostly (feed, depth of cut) [13]. The basis of the calculation is the general mathematical model of single point cutting tools [14], the essence of which is to design such a general mathematical model, which contains all of the edge sections, which a realistically possible cutting tool can have. By placing this model into a Descartes coordinate system, equations of the respective cutting edges can be described, and the generated roughness profiles can be determined by taking the kinematics of the actual cutting procedure into consideration. The method was firstly introduced for turning [15], and then its improvement was performed for face milling [13].

It was established during the previous researches where tuning was concerned [15], that the factors which affects the surface roughness at most are the geometry of the tool and the work piece and from the applied technological parameters are the feed (feed per tooth in case of milling) and the cutting speed. While face milling is a machining method done by a multi-point tool, here the radial and axial difference of the cutting edges according to each other should be also considered. During the research, those parameters were investigated, which affects the theoretical values directly, the other parameters can be taken into consideration by the application of correction coefficients. Therefore the worked-out method is general, but the results are valid only for identical tool/material pairing.

Those surface roughness characteristics were considered during the investigations which are applied at practice most commonly: the R_a arithmetical average roughness and the R_z average distance between the highest peak and lowest valley parameters, but any surface roughness index can be calculated by the application of the elaborated method.

Experimental conditions

Cutting experiments were performed to determine the real roughness data, and roughness of the surfaces generated by the special face milling were measured. The conditions of the conducted experiments will be introduced.

The experiments consist from two test series (Test A and Test B), which were performed with the specially designed milling head (Fig. 1). In Test A two identical circular inserts were placed into the milling head. The inserts seats are machined into custom shafts which then clamped

into the holes on the base body. In the current tests, only two inserts were used, but the milling head can hold four cutting inserts simultaneously (Fig.1/a).

In Test B, the face milling was performed by two cutting inserts with different edge geometry. While the height of the inserts is significantly different from each other in this case, therefore it is extremely important to take the axial and radial differences into consideration. The ability to plan is important, because the roughness values on face milled surfaces depends on the direction of the measurement and also in case of measuring at the feed direction on the actual location of the inspection.

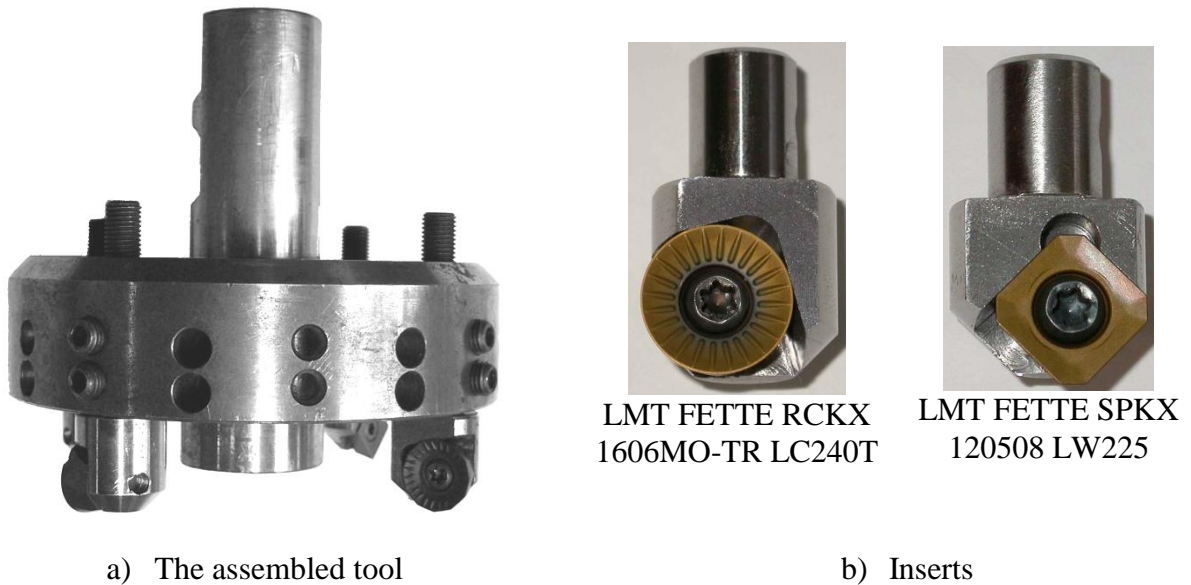


Figure 1. The tools applied for the experiments

The two insert geometries (circular and rectangular) which were applied at cutting experiment can be seen in Fig. 1/b fixed at the cylindrical insert holder. The investigations were performed on a Maho MH 600E milling machine with CNC 432 control. The material of the specimens was 42CrMo4 alloyed heat treatable steel. The specimens were in quenched and tempered state, tensile strength was about 1080 N/mm², and their hardness was around 320 HB. The hardness values of the specimens were inspected with a Mitutoyo MVK-H1 hardness testing machine with measuring force of 10 N. The specimens were formed as 50x50x100 mm blocks. The goal of the first set of the cutting tests (Test A) was to investigate the roughness of surfaces machined by two identical inserts. For the clear identification of the insert marks on the machined surface, relatively high feed rate values were applied (which were selected by taking the insert manufacturer's recommendations into consideration), while the cutting speed was relatively low (Table 2). The goal of the second series of experiments (Test B) was to investigate the surface roughness after face milling with a cutter holding different insert geometries simultaneously. The cutting parameters should be refined in this test in order to minimize dynamical effects of the cutting process (Table 2).

Table 2. The applied technological parameters

	Test A	Test B
Cutting speed v_c [m/min]	100	160
Depth of cut: a_p [mm]	1	0.5
Width of cut a_e [mm]	50	50
Feed per tooth f_t [mm]	0.21, 0.64, 1.06, 1.48, 1.92	0.1, 0.2, 0.3, 0.4, 0.5

The assembled cutting tools were measured in a Zoller V420 tool pre-setting equipment.

Experimental results

Determination of theoretical values were performed by a computer software which was created on the basis of the developed calculation procedure [13]. The measurement of cut surfaces were done by the AltiSurf 520 surface roughness tester analyzer equipment which can be found at the Institute of Manufacturing Science at the University of Miskolc. Recommendations of the EN ISO 4288:1998 and EN ISO 3274:1998 standards were followed during the measurements.

The theoretical and real profiles in Fig. 2 are shown for $f_t = 1.48$ mm in case of application of two identical circular inserts (Test A). The axial run-out of the inserts was $65 \mu\text{m}$ according to measurements with the previously introduced tool pre-setter device, which can be directly seen on the measured profile too. The theoretical roughness profile was calculated according to this argumentation.

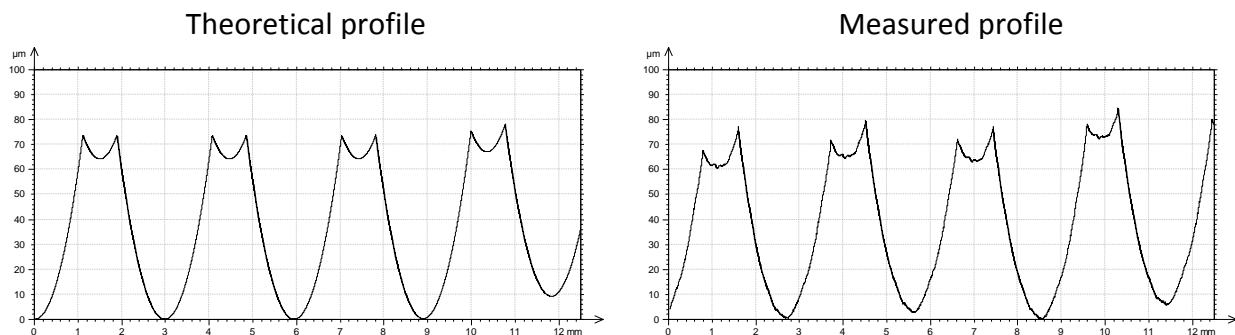


Figure 2. The theoretical and measured profiles in Test A for $f_t = 1.48$ mm

Comparison diagrams of theoretical and real values of Ra and Rz parameters can be seen for Test A in Fig. 3 in case of application of two circular inserts with identical geometry. A drop of roughness values can be observed in both diagrams around feed per tooth of 1.5 mm. The reason for that phenomena is the following: the previously mentioned axial run-out values were greater than the maximum roughness peaks at low feed per tooth values – thus the roughness peaks are repeated at $2 \times f_t$ intervals at feed per tooth values which are below $f_t = 1.48$ mm, and when the second insert enters into cut, the cusp height decreases. This will affect both parameters, but of course the drop is higher for the Rz parameter, which is directly calculated from the cusp height.

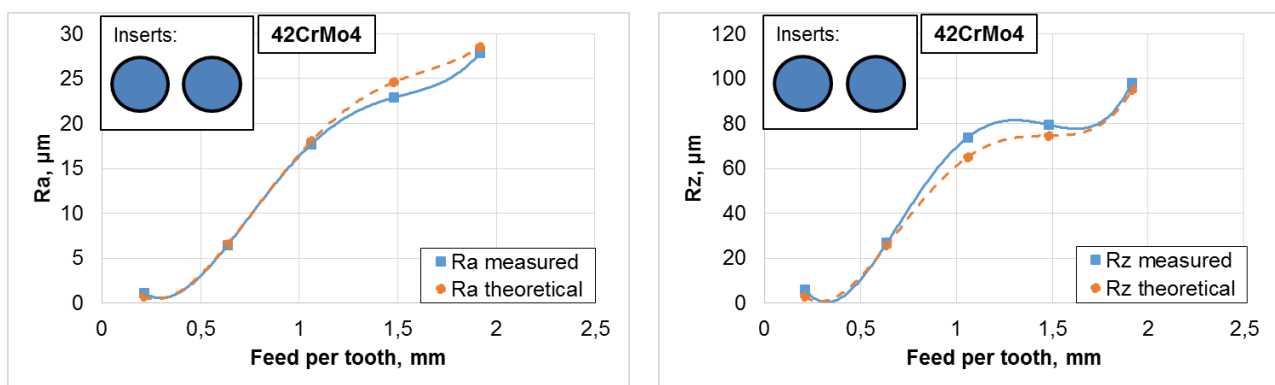


Figure 3. Comparison of theoretical and measured values of Ra and Rz parameters for Test A

In the second experimental test series (Test B) two different cutting inserts were applied, and the axial position of the inserts were adjusted with the tool pre-setter device.

A sample theoretical and a measured profile can be seen in Fig. 4. It should be mentioned, that the similarity between theoretical and real profiles is increases with the feed value.

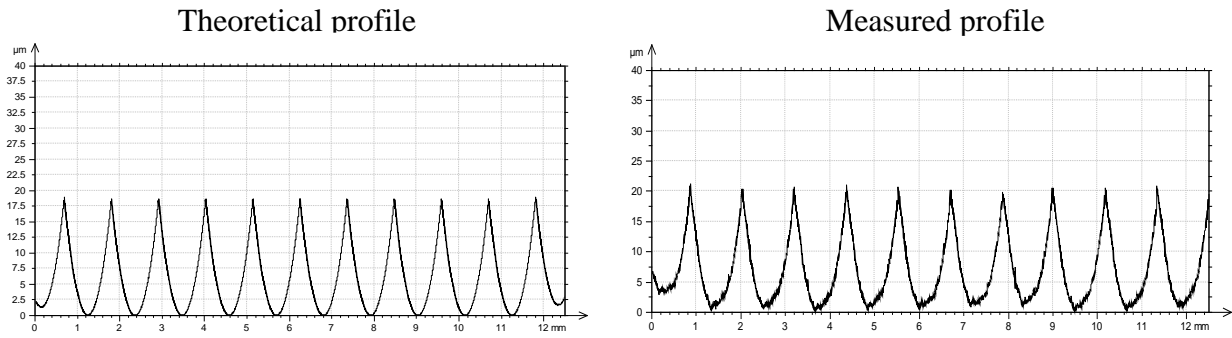


Figure 4. The theoretical and measured profiles in Test B for $f_t = 0.5$ mm

Looking at the roughness diagrams in Fig. 5 it can be stated, that there is no setback as it was on the previous case. It can be also followed that the real roughness approaches the theoretical values with increasing of feed, and even it go below it in case of arithmetical average roughness. This phenomena can be attributed to the plastic deformation which occur during the cutting process and the effect of vibrations.

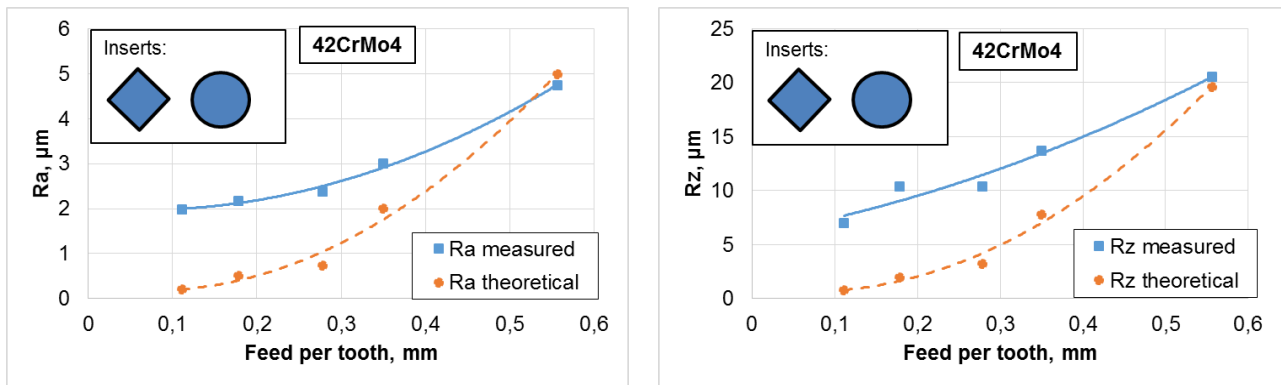


Figure 5. Comparison of theoretical and measured values of Ra and Rz parameters for Test B

In order to make it possible to plan the surface roughness, the relations between theoretical and measured data were determined by the help of regression analysis.

Experience has shown that it is practical to provide the approximation by power function:



$$R_{(a,z,t)real} = C_1 \cdot (R_{(a,z,t)theo})^{C_2} \quad (1)$$

where:

- $R_{(a,z)real, theo}$: real (estimated) and theoretical (calculated) value of the respective roughness parameter (Ra or Rz);
- C_1, C_2 : coefficients.

The calculated regression coefficients for the two tests and the pertaining coefficient of determination (R^2) values are summarized in Table 3.

Table 3. Regression constants and coefficients of determination

Inserts	Ra			Rz		
	C_1	C_2	R^2	C_1	C_2	R^2
	1.461	0.859	0.997	2.542	0.792	0.989
	2.754	0.268	0.915	7.686	0.314	0.971

Summary

The article is presented a method for modelling the surface roughness, the basis of which is the determination of theoretical roughness values, and to set up relations with real roughness data observed during cutting experiments. The application of this method were presented with experiments carried out in two specific cases of face milling: cutting with two identical circular inserts as well as with a rectangular and a circular inserts simultaneously. Theoretical values of Ra and Rz were determined for the investigated range of feed rate. Roughness values measured after cutting experiments carried out by varying the feed was evaluated and compared with the theoretical values graphically. The relations were defined between the theoretical and real values which were measured during the cutting experiments. By the help of these relations the real values can be planned for other cutting data on the basis of theoretical values. Practically any theoretical surface roughness characteristic can be calculated with the help of the previously worked-out method. The authors are currently working on the improvement of the method to be applied in other machining processes.

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