3D roughness parameters of surfaces face milled by special tools

Janos Kundrak, Csaba Felho
Institute of Manufacturing Science, University of Miskolc. Egyetemvaros, 3515 Miskolc. Hungary. E-mail: janos.kundrak@uni-miskolc.hu, csaba.felho@uni-miskolc.hu

At design of cutting tools the positioning of cutting edges and geometry of cutting inserts are becoming increasingly diversified with the development of cutting procedures. As a result, the generated tool marks on cut surfaces also can take many forms. Roughness values in face milling can change both in planes parallel with the feed direction and in planes at angle to it, therefore it is particularly important to be able to plan the roughness characteristics of surfaces. A new method is introduced in the paper for planning the roughness characteristics of cut surfaces that can be used to determine theoretical values of roughness characteristics of surfaces generated by tools having defined edge geometry. It is based on CAD modelling of the theoretical cut surface; practically any complex tool geometry can be modelled and 3D roughness parameters determined. In application of rotating tools a variety of tool designs and setting accuracy were taken into consideration during the determination of theoretical values for the simultaneous cutting of more than one edge. An example is shown for two different insert geometries.

Keywords: Roughness, Milling, Tool geometry

1. Introduction

When planning finishing machining, the aim is to ensure the ability to plan as many characteristics of machined parts as possible (to ensure compliance with operational requirements), to select optimal values, and to ensure the economy and reliability of manufacturing processes.

In finishing machining, microgeometry of the cut surface is an important characteristic of the surface quality of parts, as it has significant effects on the tribological properties of functional surfaces and on the lifespan of parts. Surface geometries generated during machining are becoming more diverse due to the increasing variety of solutions evolving in tool design and in the positioning of the cutting edges on a tool body, as well as their edge geometry. Therefore, the investigation of the micro-geometrical characteristics and roughness indexes of surface topography generated by different cutting procedures is one important direction of research. Such studies are aimed at defining tooling and technological conditions for the selection of machining procedures to ensure optimal surface roughness.

A good overview of progress in this field can be found in [1], where modelling procedures and techniques for surface roughness and surface integrity are categorized into analytical, numerical, experimental and artificial-intelligence based methods for investigating surface roughness, quality and integrity. A systematic approach is presented in [2] for modelling the milling process geometry with cutter run-out based on the true tooth trajectory of cutter in milling. A simulation study of the effects of cutter run-out on milling process geometry was conducted using the models. Surmann and Biermann [3] developed a geometric model for predicting surface formation resulting from peripheral milling processes when tool vibration is present. This model enables the prediction and minimization of the roughness and location errors of the flank surface. An experimental work in [4] investigated the effects of different insert radii of cutting tools, different depths of cut and different feed rates on the average surface roughness when dry turning AISI 1030 steel. Factorial design was used in [5] combined with techniques of regression for modelling the behaviour of surface roughness depending on several variables, namely cutting speed, feed and depth of cut. An integrated Simulated Annealing (SA) – Genetic Algorithm (GA) approach was applied in [6] to estimate the optimal solutions of cutting conditions that lead to the minimum Ra value. Surface roughness is analysed for every machining procedures including abrasive processes [7]. Typically, 2D and 3D parameters of cylindrical surfaces are investigated [8], but there are ongoing researches for milling too [9].

An easily manageable and multi-purpose solution is introduced here for the prediction of the expected roughness, which is based on theoretical values of roughness indexes. The calculation method allows the analysis and mathematical description of the connection between theoretical and measured roughness indexes when cutting by tools with geometrically defined cutting edges as well as the ability to plan the roughness. Roughness of surfaces milled under different experimental conditions is compared with the calculated theoretical values, and their relationships are determined.

2. Determination of theoretical values of roughness indexes

Theoretical roughness can be determined analytically based on the kinematics of the process and tool geometry. Theoretical values of surface roughness are interpreted in the main reference plane of the tool; values are found by tool placement edges determined in the plane and cutting data (feed, depth of cut) [10].

In face milling, a cycloid is described by the teeth of the milling cutter in the workpiece coordinate system due to the motion combination specific to milling. These cycloids are positioned at a distance determined by the feed, and two such cycloid sections delimit the chip removed by the tooth. Due to these kinematical conditions, different roughness values are created in the different directions and points of the surface and are determined by the relative motions (Fig. 1) [11].

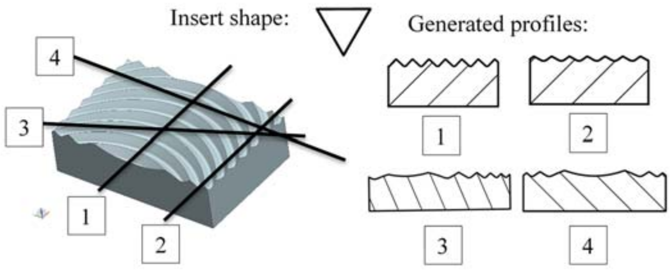


Fig. 1 *Tool imprints generated on surfaces machined by face milling cutter*

To introduce the general application possibility of the method for roughness analysis in machining with rotary tools, investigations were performed with a special face milling design employing cutting inserts with different edge shapes. This tool was developed by researchers led by Prof. Karpuschewski [12].

The periodic surface elements that are created during one rotation of the tool with varied inserts are relatively complex, even in the feed direction (Fig. 2).

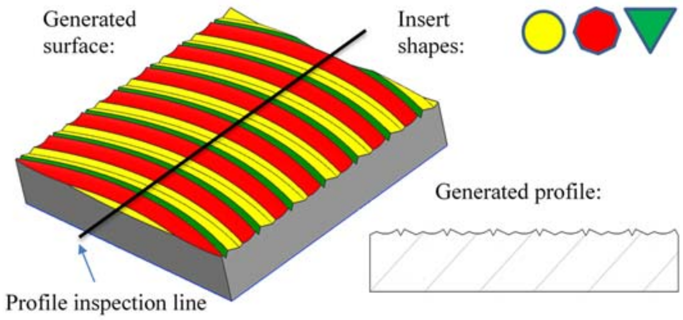


Fig. 2 *Theoretical topography of a surface milled by tools with different geometries*

In face milling, the relative difference of cutting edges should be taken into account both in axial and radial directions. The goal was to elaborate a general method for the theoretical description of surface topographies which can be applied in every case represented in Fig. 3.

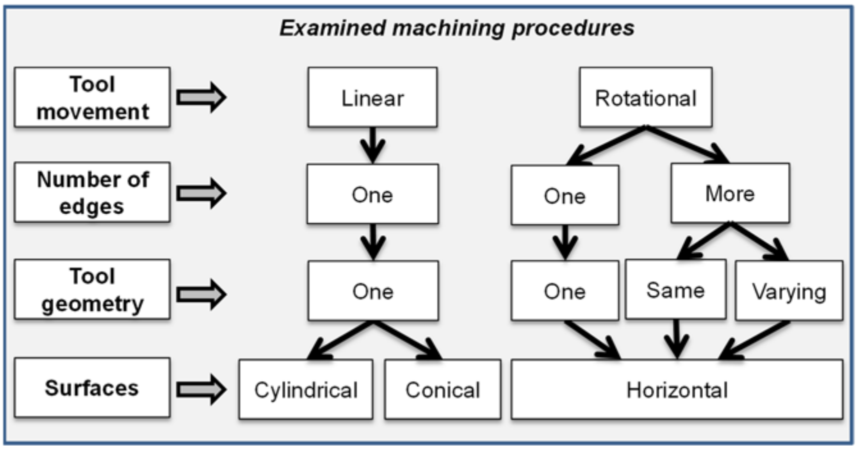


Fig. 3 *Summary of the investigated cases*

3. Investigation method

The applied method is the determination of theoretical and real roughness indexes and the revealing of the relation between them.

The calculation method which was proposed and applied here [13] aimed to:

- be capable of determining all roughness indexes that can be calculated theoretically;
- be capable of comparing cutting tools with different geometries based on the roughness;
- describe the relation between them by the comparison of theoretical and measured values;

- predict roughness indexes for tools with arbitrary profiles.

3.1 Mathematical model of the cutting tool

The basis of the calculation is the general mathematical model of cutting tools [10]. The essence is to create a tool model from which the geometry of all realistically possible cutting tools with defined edge geometry can be derived. Equations of the cutting edges can be described in the main tool reference plane by putting this model into an X-Y coordinate system, and the roughness profiles generated by the edges can be determined by taking the kinematics of the cutting procedure into consideration.

The tool geometry of commonly applied cutting tools can be mapped in the tool main reference plane by this method. Calculation can be performed by three different methods: analytically, numerically or by CAD modelling. CAD modelling is the most suitable for determination of 3D roughness [11].

3.2 CAD modelling

A 3D simulation model of face milling was created in the Autodesk Inventor CAD system. Here both the workpiece and the tool geometry were modelled in the CAD system, and then the cut surface was generated by applying the actual kinematics of the cutting process and by subtracting the removed material from the workpiece. This 3D model can visualise the generated surface and transfer the roughness surface into the AltiMap (Mountains®) professional surface imaging and metrology software with an interface program (Autodesk Inventor Add-In) developed to store the points of the surface with given accuracy (x and y resolution) into a suitable binary file format (SURF file format from Digital Surf). The benefit of this transfer is that the roughness indexes of theoretical and real surfaces can be calculated and visualised in conformance to standards and on the same basis.

3.3 Relation of theoretical to real roughness

Real roughness data of surfaces machined with the conditions intended for comparison are needed for prediction of roughness. Thus, cutting experiments are performed with the given (investigated) tool geometry and actual values of the machined surfaces are measured. Comparative analyses have two purposes: (1) validation of theoretical values obtained by calculation, and (2) determination of the relation between calculated theoretical and measured values and their mathematical description.

Theoretical values will deviate from actual values, as factors such as the material quality to be cut, tool material, vibration, cooling and lubrication will influence the real roughness. The roughness of machined surfaces can be planned in advance by defining the relation between theoretical and real roughness data.

4. Experiments

Cutting experiment were conducted to determine real roughness data; machining conditions and cutting data were adjusted in the milling machine with different feed values and insert variations.

Tab. 1 *Data and order of the applied cutting inserts*

Insert shape	Square	Dodecagonal
Type	LMT FETTE SPKX 120508 LW225	LMT FETTE XCKX 1606 ZDR-TR LC240T
Insert size (iC), [mm]	12	16
r_ε, [mm]	0.8	0.5
Cutting edge angles	$\kappa_{r1} = 45°$ $\kappa_{r1}' = 45°$	$\kappa_{r1} = 15°$ $\kappa_{r1}' = 15°$
Effective diameter in Tool B, [mm]	104.21	107.50

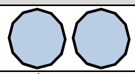
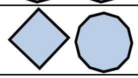
4.1 Experimental conditions

The milling head was modified from a previous milling head design [14] and accepts inserts with either identical or different edge geometries. Two inserts with different geometry were applied (Table 2). First one insert was fixed in the milling head, then two identical ones, and finally two different inserts, in the order indicated in the table.

Position of the insert pitch point: Because the cut surface is generated in face milling by multiple cutting edges, the created topography is influenced by the adjustment accuracy of the respective inserts, the number, and the order of inserts. This is particularly true for inserts with different edge geometries [13].

The axial and radial positions of the inserts were adjusted by a Zoller V420 type optical tool pre-setter device. The first (square) insert was treated as the basis during measurements and in calculations, thus its setting errors are zero. The radial and axial run-outs of the second inserts are presented in Table 3. See Table 2 for absolute positions of the insert pitch points and their effective (working) diameters.

__Tab. 2__ Insert setting deviations for application of more than one insert

Inserts	Run-outs
	e_{rad} = 0.9 µm, e_{ax} = 115 µm
	e_{rad} = 1.645 mm, e_{ax} = 1.1 µm

Workpiece properties: The material of the specimens was 42CrMo4 alloyed heat treatable steel. The samples were in quenched and tempered state, tensile strength was 1080 N/mm^2, and hardness was 320 HB. The specimens were formed as 50x50x100 mm blocks; their 50x100 mm sides were machined.

Machine tool, cutting parameters: Tests were conducted on a Fritz Heckert FQ 400 vertical milling machine with cutting speed v_c = 160 m/min, depth of cut a_p = 0.5 mm, and width of cut a_e = 50 mm (0.74 x D_m).

The varied parameter was the feed per tooth: 0.111, 0.175, 0.278, 0.35 and 0.556 mm/tooth, from the realised v_f data.

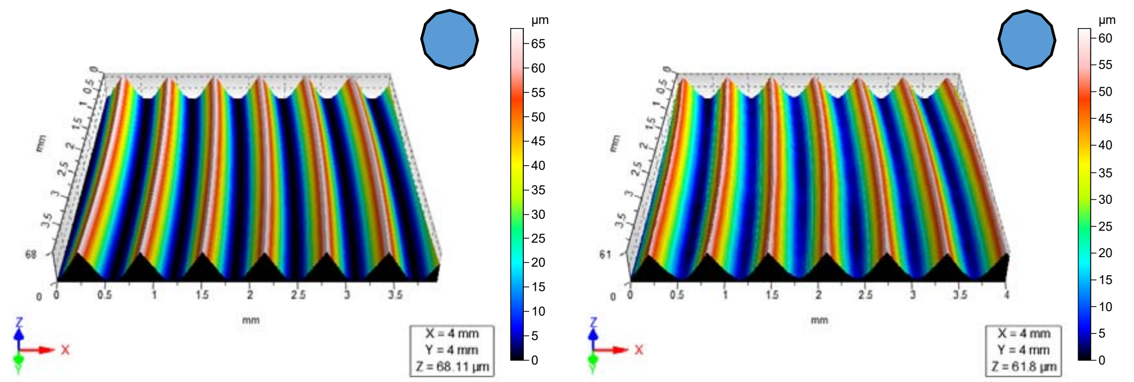
4.2 Surface roughness measurements

Roughness characteristics of the surface were measured after the completion of the cutting experiment. Measurements were performed on an AltiSurf 520 three-dimensional surface roughness measuring apparatus. The measurement parameters were according to the ISO 25178 standard. Numerical values were determined as averages of three measurements.

The tool model was created with the experimental data, then the theoretical surface was generated with the CAD model, and then theoretical values of roughness indexes were determined wit AltiSurf by exporting the surface into it as mathematical points. Calculated theoretical values were then compared with roughness data measured at cut surfaces of experimental parts.

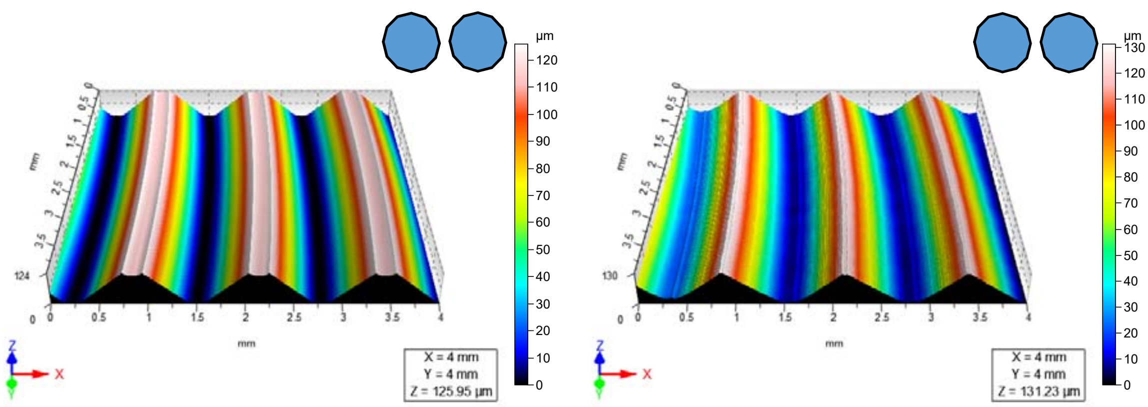
5. Experimental results

Theoretical (a) and measured (b) roughness surfaces milled by a single dodecagonal insert can be seen in Fig. 5 and for two dodecagonal inserts in Fig. 6. The similarity of the two roughness surfaces is clear.



a) Theoretical surface *b) Measured surface*

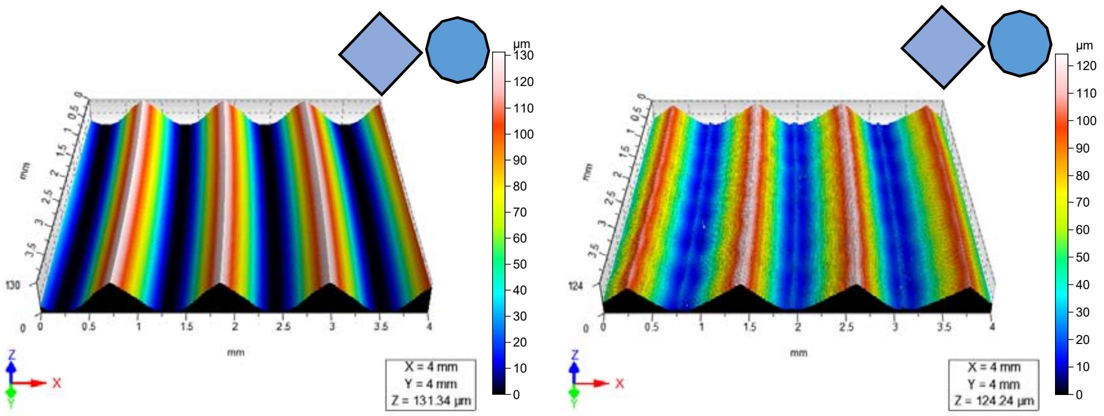
Fig. 5 *Theoretical and measured surfaces for one dodecagonal insert, feed per tooth f_t = 0.6 mm*



a) Theoretical surface *b) Measured surface*

Fig. 6 *Theoretical and measured surfaces for two dodecagonal inserts, f_t = 0.6 mm*

On the roughness surfaces shown in Fig. 7 for differently-shaped inserts it can be seen that one tool is determinative in the formation of the roughness caused by the different insert setting values. Traces are visible of minimal vibration, which occurs during chip removal.



a) Theoretical surface *b) Measured surface*

Fig. 7 *Theoretical and measured surfaces for a square and a dodecagonal insert, ft = 0.6 mm*

6. Comparison of theoretical and real roughness data

The arithmetical mean height of surface (Sa) and the maximum height of surface (Sz) were compared from the 3D roughness indexes [15]. It can be seen that in the first two cases (Figs. 8 and 9) the values change identically as functions of the feed.

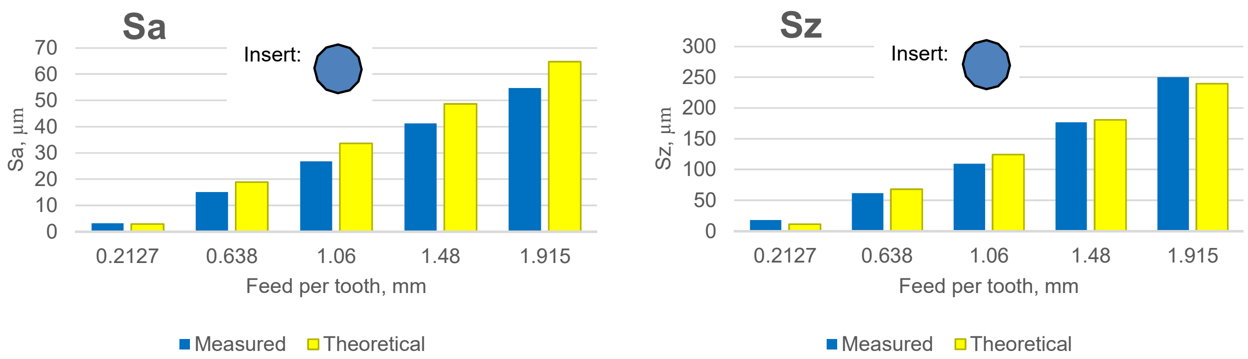


Fig. 8 *Sa and Sz indexes versus feed for one dodecagonal insert*

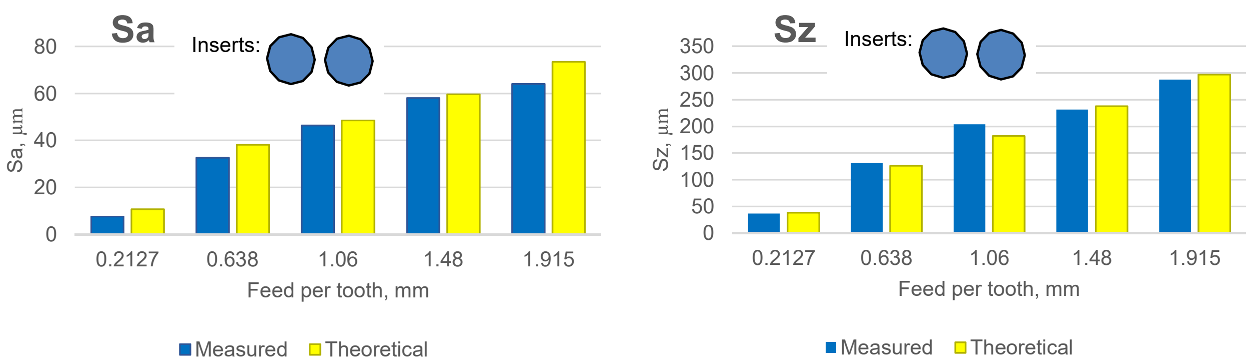


Fig. 9 *Sa and Sz indexes versus feed for two dodecagonal inserts*

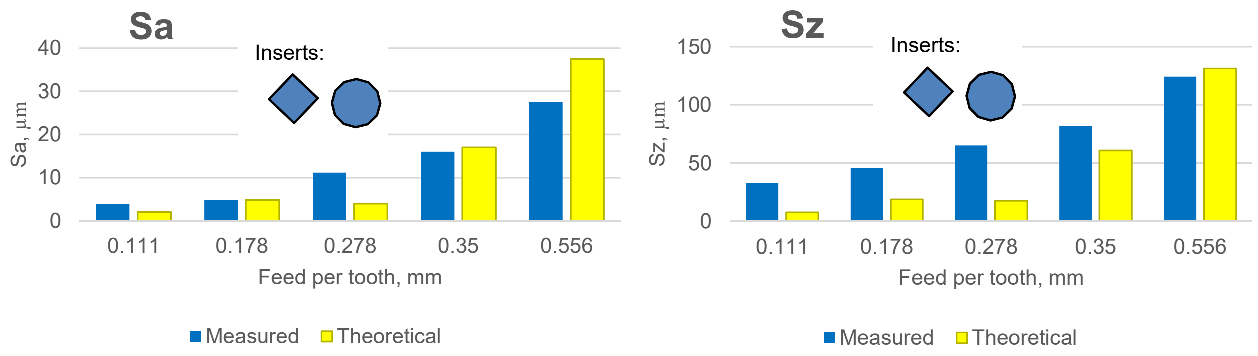


Fig. 10 *Sa and Sz indexes versus feed for different insert geometries*

In Fig. 10 the theoretical roughness changes more strongly as a function of feed, which may be due to the surfaces which can be seen in the 3D view in Fig. 7.

7. Applicability of results for predicting of roughness

We found that there is a relatively simple functional relationship between theoretical and measured values. However, it should be emphasised that the level and character of the adequacy between the two characteristics as well as the amount of their change depend on actual cutting conditions. Relations of certain parameters are shown in Figs. 11-13.

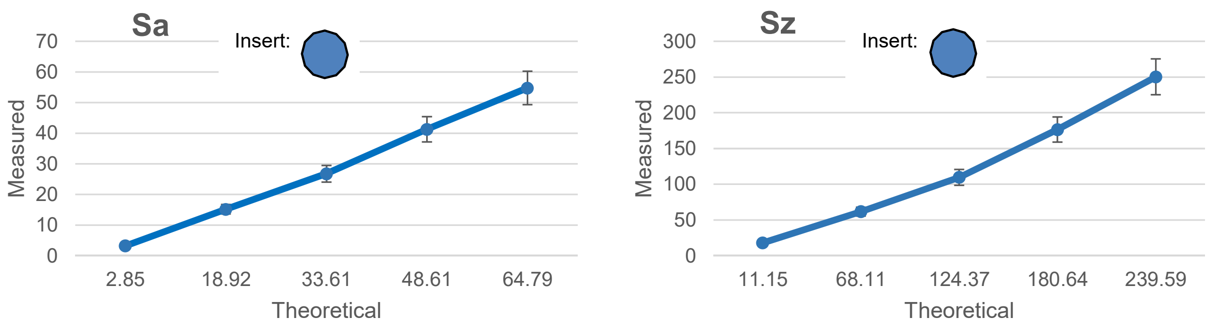


Fig. 11 *Correlation between theoretical and real values of Sa and Sz indexes versus feed for one insert*

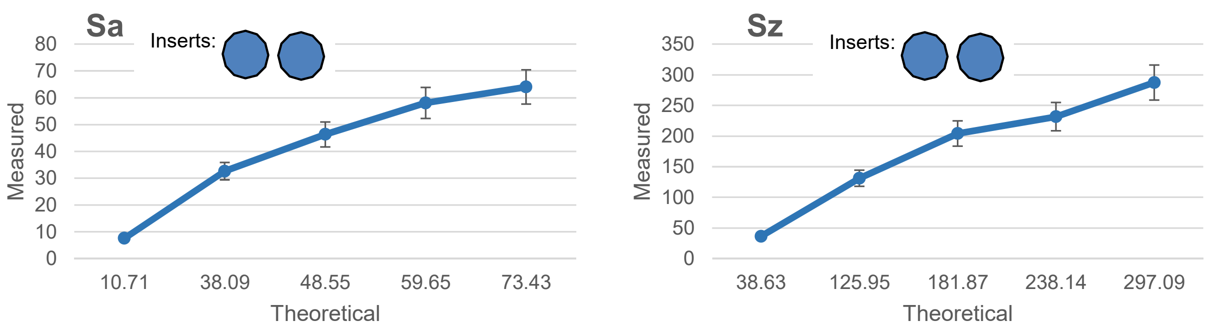


Fig. 12 *Correlation between theoretical and real values of Sa and Sz indexes versus feed for two identical inserts*

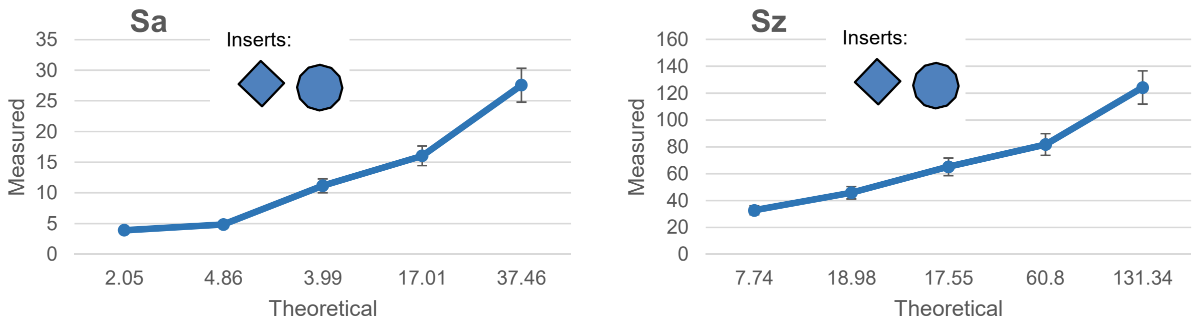


Fig. 13 *Correlation between theoretical and real values of Sa and Sz indexes versus feed for two differently-shaped inserts*

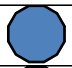
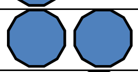
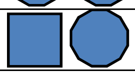
If this relation is described with the simplest formula of engineering practice, then by applying a power function a comparatively precise determination of the relationship between the two roughness data can be obtained.

$$y = C \times X^a \tag{1}$$

Where:
y: real (predicted) value of the respective (Sa or Sz) roughness parameter [µm],
x: theoretical (calculated) value of the respective roughness parameter [µm],
C: regression constant [-],
a: exponent [-]

The calculated constants and exponent values are given in Tab. 3.

Tab. 3 *Calculated regression constants and coefficients*

Param.	Sa			Sz		
Coeff.	C	a	R^2	C	a	R^2
	1.197	0.9	0.995	2.140	0.840	0.981
	0.513	1.144	0.995	0.908	1.021	0.993
	2.735	0.632	0.822	14.29	0.440	0.913

8. Summary

A method was introduced for the comparison of theoretical and real values of roughness indexes and determination of relationships between them. With this the topography of a face-milled surface can be analysed in detail. The method allows:

- demonstration of the periodicity of roughness characteristics at the centreline of the tool in case of rotary tools, and the determination of the various roughness characteristics in planes parallel to the feed direction;
- presentation of the change of roughness values in different measurement directions and the determination of concrete values;
- determination of theoretical roughness characteristics when using rotational tools with inserts with different geometries;
- comparison of theoretical values with the described method and formulation of mathematical connections between theoretical and real roughness values.

These capabilities provide an up-to-date method for the planning of the roughness of surfaces to be machined and for the determination of theoretical values of 3D roughness indexes by mathematical formulas defined through experimental results.

Acknowledgements

The authors would like to express their thanks to the IFQ Institute of the Otto-von-Guericke University for its support during the realisation of the experiments. This research was partially carried out in the framework of the Center of Excellence of Innovative Engineering Design and Technologies at the University of Miskolc. The authors greatly appreciate the financial support of the National Research, Development and Innovation Office – NKFIH (No. of Agreement: OTKA K 116876).

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