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CAD-Based Modelling of Surface Roughness in Face Milling

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Abstract**—**The quality of machined surfaces is an important characteristic of cutting processes and surface roughness has strong effects on the performance of sliding, moving components. The ability to forecast these values for a given process has been of great interests among researchers for a long time. Different modeling procedures and algorithms have been worked-out, and each has its own advantages and drawbacks. A new method will be introduced in this paper which will make it possible to calculate both the profile (2D) and surface (3D) parameters of theoretical roughness in the face milling of plain surfaces. This new method is based on an expediently developed CAD model, and uses a professional program for the roughness evaluation. Cutting experiments were performed on 42CrMo4 specimens in order to validate the accuracy of the model. The results have revealed that the method is able to predict surface roughness with good accuracy.

Keywords**—**CAD-based modeling, face milling, surface roughness, theoretical roughness.

I. INTRODUCTION

NOWADAYS the continuous evolution of machining processes can be observed, which leads to even stricter quality demands for machined parts. Meeting these demands is usually not an easy task, especially when taking into account that part geometry is becoming more and more complex. One important parameter of the qualification of machine parts is the quality of machined surfaces, which has great importance primarily in the case of mating, sliding elements [1]. The topography of surfaces and its formation is essential, since it will determine the lifetime of the part through several factors, including tribology and bearing ratio.

At the same time the quality of machined surfaces is a complex concept, which includes its microgeometry (in other words, its surface roughness), its stress state, and hardness among others. Therefore there is a constant demand from the side of production engineers to develop methods which can help to predict the expected quality of machined surfaces and thus to choose the optimal process from the available resources, and to select the most suitable process parameters [2]. The ability to plan the surface roughness is very difficult in general, although the measurement procedures are getting more and more sophisticated and accurate, but it is still important to determine its theoretical values. These values were determined for the first time by trigonometry [3], where often complicated formulas were established. Advances in computer technology have opened new opportunities, since numerical methods [4] and soft computing techniques [5] can now solve very complicated problems. In addition, usually standard tools with standard kinematics were considered during the previous approaches [6], that is, they were concerned with traditional machining processes. Numerous researchers had contributed to this area of research, and a comprehensive summary of the applied models in surface roughness prediction can be found in [7]. The applied models can be essentially classified into four groups:

- analytical models and computer algorithms;
- experimental methods;
- methods based on designed experiments; and
- artificial intelligence models.

All of these methods have their advantages and disadvantages, so there is no single perfect solution. However, it was concluded in [8], that the most promising solutions are the different analytical models combined with robust computer algorithms and AI-based approaches. In accordance with that, the model which will be introduced here can be characterized as an analytical model-based computer algorithm.

Such a new method is introduced in this paper for the modeling of theoretical surface roughness of machined parts, which is suitable for the determination of virtually any 2D or 3D parameter of surface roughness with the help of professional surface roughness evaluation software. The cutting process which is examined here is face milling, but the model can be easily adapted to virtually any machining process with single- or multi-point tools. This model is based on the CAD representation of the machined surface, which will be exported to a special format (SURF) in order to make it possible to import this data into professional surface roughness evaluation software. The main advantage of this method is that it makes it possible to handle arbitrary tool geometries and that any standard 2D or 3D surface roughness parameter can be determined with it. By transferring the coordinate points of the surface into the roughness evaluation software, the theoretical surface roughness values can be determined on the same basis as measurement data were evaluated, and therefore their comparison becomes easier. This method was worked out as a result of a long-term research study on prediction of surface roughness on surfaces machined by single and multi-point cutting tools. The first investigations were performed for hard turning processes [9]-[12], and then the focus was moved towards face milling of horizontal surfaces [13]. The basis of these investigations was the general mathematical model of single-point cutting tools [9], which also serves as a basis for the development of the

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introduced method. The basic workflow of the developed method is introduced below.

II. Method for the Prediction of Surface Roughness in Face Milling

The main goal of the investigation was to determine relations between the theoretical and measured values of surface roughness. The method for the calculation of theoretical values was to create a CAD model which simulates the face milling process. Surface points of this model can be exported to a special format, which is called SURF file format. This format is used by majority of surface roughness tester equipment manufacturers to exchange measured data. A special interface program is developed for this task, which is able to communicate with the CAD system, and will retrieve coordinates of the needed points and store them into the output file. This file can be evaluated with the software AltiMap. Then the theoretical roughness indices will be determined by the software from surface points. The real (measured) roughness data can be obtained from cutting experiments, and then the relation between them can be evaluated by the help of regression analysis. A flowchart of the method can be seen in Fig. 1.

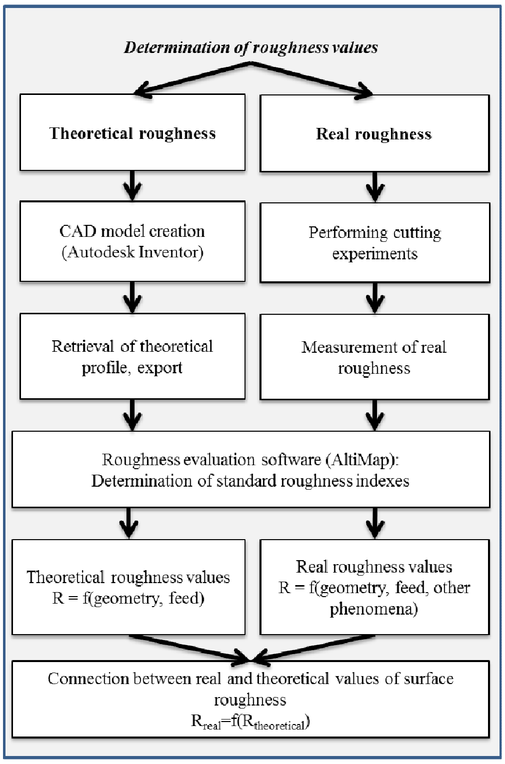


Fig. 1 Flowchart of the developed method

This method allows the prediction of the roughness values of surfaces for a given tool – material pairing when cutting with exactly the same cutting conditions (machine, tool, workpiece characteristics, cutting data, etc.).

III. CAD-Based Simulation of the Theoretical Roughness

The 3D simulation model of face milling was created in the Autodesk Inventor CAD system. This method is somewhat similar to that which was introduced in [14]. This 3D model is suitable both for to visualizing the generated surface and for transferring the roughness surface into the AltiMap software using an expediently developed interface program. The basic flowchart of the worked-out method can be seen in Fig. 2.

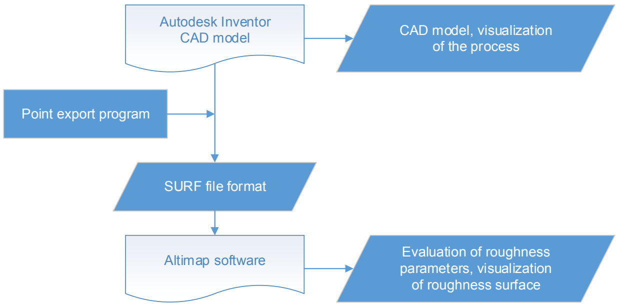


Fig. 2 Flowchart of the developed CAD-based modelling method of surface roughness

First the 3D simulation of the face milling process was developed, by which the theoretical surface can be generated. Steps of the model creation were the following:

1. Creation of a model of the workpiece: a rectangular solid. The built-in “Box” command was used for this step in the system. The coordinate system convention followed during the creation of the model is that which is generally applied in milling machines, where the x-axis is in the feed direction, the y is perpendicular to this in the plane of the table, and the z-axis is in the vertical direction (Fig. 3).

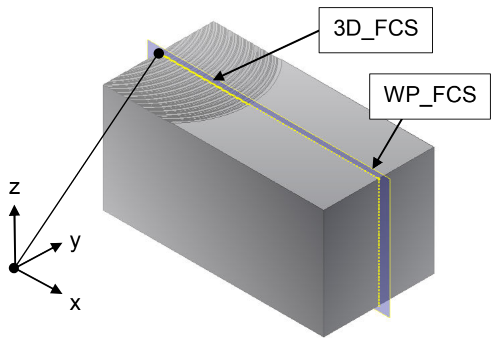


Fig. 3 The generated 3D model of the workpiece with the coordinate system

2. Creation of the planar shape of cutting inserts in the x-z plane. Axial and radial locational errors are also considered during the positioning of the inserts. In the case of modeling a milling head with several inserts, they should be drawn separately shifted in the x-direction with

the feed per tooth value (f_t) to each other corrected by the respective run-out values.

3. Description of the curtate cycloid path which is the resultant of the rotational main motion and the linear feeding motion by the "Equation curve" command in the "3D Sketch" menu. When modelling several inserts the cycloids which corresponding to the respective inserts can be created individually (in the case of radial run-outs) or a previously created one can be multiplied by the "Pattern feature" command with the spacing which corresponds to the f_t value.
4. Sweeping the shapes representing the inserts on the resulting tool path by the "Sweep" command, thus simulating the real cutting process. The resulting bodies should be subtracted from the workpiece with the "Cut" option of the "Sweep" command.
5. Finally these cuts should be multiplied with the "Pattern feature" command, where the spacing can be either the feed per revolution value f or the feed per tooth f_t. Thus, as many tool paths can be created, as are needed for the evaluation of the roughness surface.

The generated 3D model of the workpiece with the cut surface topography can be seen in Fig. 3. Here the "WP_FCS" workplane and the "3D_FCS" 3D sketch are also indicated; those will intersect the generated surface and their intersection curve will represent the theoretical roughness profile. The user has to define the x and y dimensions of the investigated area (Fig. 4).

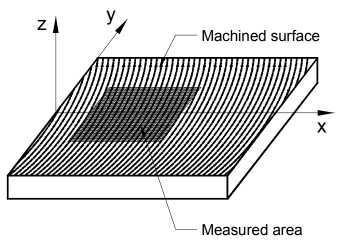


Fig. 4 The evaluated area on the machined surface

The spacing values in x and y directions are also has to be defined by the user (Fig. 5).

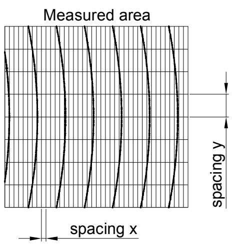


Fig. 5 The x and y spacing of the surface

Points (x, y, z coordinates) of this profile will be asked from the CAD system with the specified x-spacing accuracy, and then these coordinates will be stored in the computer's memory. By shifting this workplane in y-direction with the y-spacing value, points of the next profile can be calculated and the whole surface can be obtained by the repetition of this process until the y-size value has been reached.

IV. Interface Program to Transfer the Points of the 3D Model into Surface Roughness Data

The above-mentioned tasks are performed by an expediently developed Add-In for the Autodesk Inventor CAD system. This interface program has a Graphical User Interface (GUI), where the user can enter input parameters such as start, size and spacing values in x and y directions; the output file path and name and the output type (profile or surface). This program is completely integrated into the base CAD system, and it can be started with a dedicated icon within that. In order to separate the different task types in the program, four modules are created (Fig. 6).

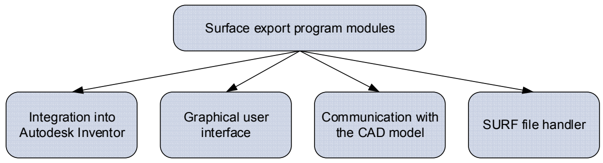


Fig. 6 The four modules of the developed Autodesk Inventor Add-In

The objectives of the four modules:

1. Autodesk Integration Module: The task of this module is to implement the integration of the program into the CAD system, to insert it into its ribbon-type user interface, and to build up the dialog windows of the program when the user clicks on its icon. The program is a so-called "Add-In" in the CAD system, which means that it will be loaded every time the system starts, and it has an icon in the system's interface with which it can be started.
2. Graphical User Interface (GUI) Module: Handling of events on the user interface (data input, buttons, etc.), and the verification of input data. If the user clicks on the "Generate" button and the input data was deemed right by a verification function, then the control is passed to the function which will query and save the profile/surface points.
3. CAD Communication Module: This module performs the communication with the CAD system and queries model data (3D coordinates of curve points) and it will also modify the model elements when necessary (in the case of shifting the datum plane at y-stepping). The received coordinates are stored in an array in the memory.
4. SURF File Handling Module: The task of this module is to transform the coordinates which are stored in the memory into proper form (since the SURF file handles the data in integer numbers, and the CAD system uses floating-point numbers) and to save them into the appropriate file format.

The exported profiles and surfaces from the developed Autodesk Inventor model can be imported to the AltiMap program for further investigation of the topography. This software was shipped with the AltiSurf 520 3D surface roughness equipment which can be found at the Institute of Manufacturing Science in the University of Miskolc as the evaluation program for the measured profiles and surfaces. The AltiMap software is an OEM version of the MountainsMap software package developed by the Digital Surf Company in France. MountainsMap is used by thousands of research institutes, laboratories and industrial facilities working on different scales and in many different sectors worldwide.

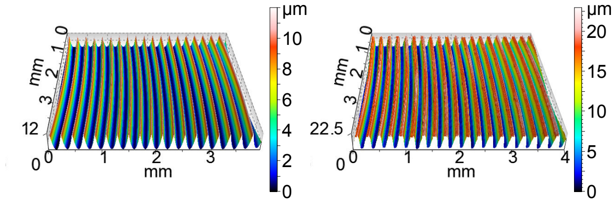
V. Face Milling Experiments and Results

In order to be able to predict the values of different roughness parameters, face milling tests were conducted and the roughness of the surfaces was measured. The tests were conducted on a MAHO MH 600E vertical milling machine with CNC 432 control. The tool was a special face milling cutter with outer diameter of $D_m = 80$mm, the cutting inserts were clamped to the tool body by special cylindrical shafts [15], the cutting insert type was OCKX1606 AD-TR, grade LC240T (octagonal insert). In order to eliminate radial and axial run-outs of the individual inserts (which of course can be included in the model, but these are not considered at this time) only one insert was used at a time; this method is also known as fly-cutting. The workpiece properties; material $42CrMo_4$ in quenched and tempered state ($R_m = 1080$ N/mm^2), geometry; 50x50x100mm block. The applied technological parameters were as follows:

- Cutting speed: v_c = 100m/min, (the rotational speed was set on the machine to n = 470 rotation/min);
- Depth of cut: $a_p = 1$ [mm];
- Width of cut: $a_e = 50$ [mm] (0.74 x D_m); recommended: 0.75 x D_m;
- Length of cut: $L_c = 100$ [mm] (total length of the workpiece);
- The varied parameter was the feed rate: v_f = 100, 300, 500, 700, 900 [mm/min], the corresponding feed per tooth values were: $f_t = 0.21$, 0.64, 1.06, 1.48 and 1.91 [mm/tooth].

The cut surfaces were measured by an AltiMetAltiSurf 520 type 3D surface roughness tester equipment. This device has 3 different measuring modes: an inductive head, a confocal chromatic probe and a laser head. The optical head was used in the current investigations, since it provides the best accuracy from the three. A CL2 probe was used with an MG140 magnifier, the resolution of this setup is 0.012 [µm]. Although many 2D and 3D roughness parameters were investigated, only two 3D parameters will be introduced here: the arithmetical mean height of the evaluated surface Sa, and the maximal height of the evaluated surface Sz. The measurement parameters were set according to ISO 4287, ISO 4288 and ISO 25178 standards. All surfaces were measured 3 times in order to eliminate measurement errors [16]. After that, the most characteristic measurement result was selected as a representation of that surface, while the roughness parameters were averaged.

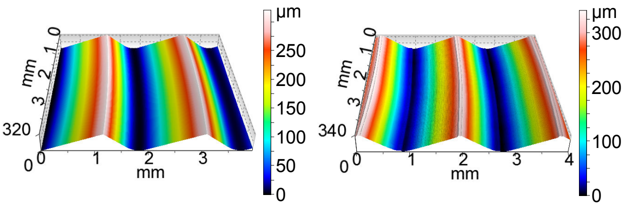
Fig. 7 illustrates the calculated theoretical (a) and measured (b) surfaces for $f_t = 0.21$ [mm/tooth]. This was the smallest value applied in the actual tests and it can be observed that the insert marks can be clearly recognized in the measured surface; however it is differs slightly from the theoretical shape. This difference can be attributed to the dynamic process characteristic of such an intermittent cutting, so it can be accepted.



(a) theoretical (b) measured

Fig. 7 Surfaces for $f_t = 0.21$ [mm/tooth]

Fig. 8 shows the simulated (a) and measured (b) surfaces for the greatest feed rate, where the corresponding feed per tooth values was $f_t = 1.91$ [mm/tooth]. Here the two surfaces are clearly identical, with very small deviations due to the large feed rate, thus the process errors are not so pronounced.



(a) theoretical (b) measured

Fig. 8 Surfaces for $f_t = 1.91$ [mm/tooth]

The theoretical and real roughness parameters were determined for each feed per tooth value, and then the results were compared. The comparison diagrams for the Sa parameter can be seen in Fig. 9. It can be observed from the graph that the two data sets have the same character.

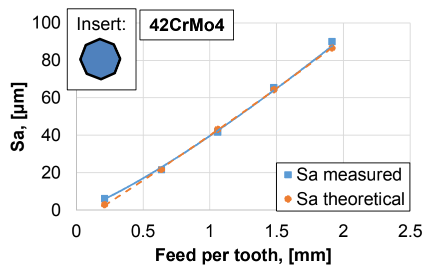


Fig. 9 Comparison of theoretical and measured values of the Sa parameter

Fig. 10 shows the comparison graph for the Sz parameter. The two data sets still have same character, but the difference between them is clearly greater, especially at higher feed per tooth values. This can be attributed again to the cutting phenomena itself: as the feed rate increases, the forces also increase, thus the whole system has much more stress which is reflected in the change of the topography of the surface.

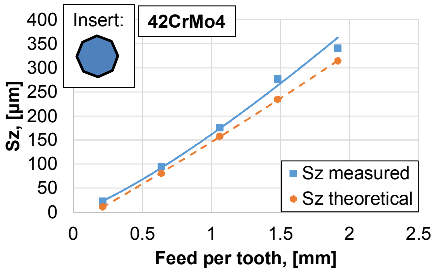


Fig. 10 Comparison of theoretical and measured values of the Sz parameter

The prediction of surface roughness can be performed by the application of regression analysis. According to previous investigations [17], [18] the regressions equation should be written in the following power form:

$$S_{(a,z)\,real} = C_1 \cdot \left(S_{(a,z)\,theo}\right)^{C_2} \tag{1}$$

where:

- S(a,z)real: Real (estimated) value of the respective roughness parameter (Sa orSz);
- S(a,z)theo: Theoretical (calculated) value of the respective roughness parameter (Sa or Sz);
- C_1, C_2: Regression coefficients.

The calculated C_1, C_2 coefficients for the two investigated parameters are summarized in Table I, together with the corresponding coefficient of determination (R^2) values.

TABLE I
REGRESSION COEFFICIENTS AND COEFFICIENTS OF DETERMINATION

	C_1	C_2	R^2
Sa	2.506	0.770	0.979
Sz	3.081	0.810	0.993

The R^2 values are very high in each case; this means that the prediction can be performed with quite good accuracy when the cutting conditions are identical to those investigated here.

VI. CONCLUSION

A new method was introduced in the paper which can be used to predict the value of any standard 2D or 3D surface roughness characteristic of machined surfaces in the case of face milling. The obtained results have revealed that the model can estimate the expectable roughness with good accuracy by using the same cutting conditions as the experimental conditions. The model has the possibility of being developed for use with virtually any machining procedure which uses single or multi-point tools with defined edge geometry.

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