

# Model for surface-roughness parameters determination in a virtual machine shop environment

N. Bilalis · M. Petousis · A. Antoniadis

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**Abstract** A virtual reality machine shop environment was developed and integrated with a graphical model for the calculation of quantitative data affecting the roughness of a machined surface. During the machining process simulation in the virtual environment, material removal and milling machine axes kinematics are visualized in real time and qualitative parameters related to the process feasibility are evaluated. The model determines the machined surface topomorphy as a cloud of points retrieved from the visualization system Z buffer and surface roughness is calculated. The current study is focused on the methodology for the verification of the quantitative data acquired by the system. Results were verified with data determined in cutting experiments and by another numerical model that was integrated into the system. The results were found to be in agreement with both the numerical model and the experiments.

**Keywords** Virtual manufacturing · Surface roughness · Machining processes simulation

## 1 Introduction

The design of production processes mainly employs two types of systems. Production processes simulation tools,

based on CAM systems and quantitative data determination tools, based on numerical, analytical, and experimental algorithms. CAM systems have limitations such as the lack of providing quantitative data and data related to the process feasibility [1]. Most of them have trivial visualization capabilities. Quantitative data determination tools also have limitations. Most of them are not integrated with CAM systems and they also provide trivial visualization capabilities. The aim of the present work is to integrate in a virtual environment the whole production design processes. A production-processes simulation system was developed for the determination of critical quantitative and qualitative process parameters that provides realistic visualization of the process in a three-dimensional virtual machine shop environment with walk/fly through and interaction capabilities. Any user of the system acquires information related to the process being simulated in the virtual environment in real time. The system extends CAM systems' capabilities, by intergrading CAM system functionalities with quantitative data determination models in a three dimensional virtual environment. The current study is focused on the methodology developed for the verification of the quantitative data acquired by the system. A two-step process was employed. First, surface topomorphy is verified and then the calculated surface-roughness parameters are evaluated. For the verification of the model results, a numerical model experimentally verified in the past [2] has been integrated into the system in order to compare its results and directly evaluate their accuracy. The accuracy of the model has also been verified with results determined in cutting experiments. The results were found to be in agreement with both the numerical model and the experiments. The verification process and its results are presented in the current study.

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N. Bilalis · M. Petousis (✉) · A. Antoniadis  
Technical University of Crete,  
Chania, Greece  
e-mail: markospetousis@yahoo.gr

N. Bilalis  
e-mail: bilalis@dpem.tuc.gr  
URL: [www.cadlab.tuc.gr](http://www.cadlab.tuc.gr)

## 2 Literature review

In this section, systems for machining processes simulation in virtual environments with surface-roughness quantitative data determination capabilities and models based on graphics technology for machining operations quantitative data determination are reviewed. Antoniadis et al. [2] presented a model for surface-roughness determination. In this model the workpiece is being modeled with vertical linear segments. As the cutter moves along the machining process trajectory, linear segments decrease their height to the lowest intersection position with the cutter edges. At the end of the simulation, linear segments vertices define the final machined surface. The model was experimentally verified and the calculated roughness levels were found to be in agreement with the experimental ones. For the verification, CK60 workpieces and P02(TiN) cutters were used. Huang and Oliver [3] developed a system for machining processes simulation in a five-axes CNC machine that is aimed at the improvement of the workpiece-machined surface quality by improving the cutter path. Ko et al. [1] developed a virtual manufacturing system for the determination of optimum feedrate values in 2.5 machining processes that provides the ability to determine cutting forces in order to improve the machined surface quality. Qui et al. [4, 5] presented a virtual reality system for material removal simulation that provides information about the required time for the completion of the machining process and quantitative data like cutting forces, surface roughness, required energy, and cutter wear. Bath University [6] developed a simulation system for several types of machining operations that could be employed for design, modeling, and implementation of production plans in the virtual environment, aiming at error detection in the executed operations. Kim et al. [7] presented a cutting force determination model for milling processes of sculptured

surfaces with ball-end cutters. In order to determine chip thickness from the intersection area between the cutter and the workpiece, a graphical method based on the Z-map was developed. Roth et al. [8] presented a cutting-force determination model for milling processes in multi-axis machines based on the Z buffer and exploits the system graphics card.

## 3 Virtual environment for machining processes simulation

The virtual environment was developed with the commercial Virtual Reality platform PTC Developer Toolkit and ANSI C programming language for the realistic visualization of the machining processes. The structure of the virtual environment is shown in Fig. 1. A complete machine shop is being visualized and the functional characteristics of a three axes CNC milling machine are being simulated. In Fig. 2 the virtual environment for machining processes simulation is presented. The user can fly through the virtual environment, interact with all the objects and manually manipulate the CNC machine. For the execution of a machining process, the user has to select workpiece dimensions and cutter from the corresponding data table. The G code program is being read from its file and the CNC machine executes the defined machining process. CNC machine axes move realistically according to the path and the feed defined in the program and spindle revolves with the predefined speed. During machining process simulation, workpiece material removal is being visualized when the cutter intersects the workpiece and data related to the process are being visualized. When the simulation is completed, user is able to select the surface-roughness measurement area in the equivalent virtual environment data table and hence acquire quantitative data for surface-

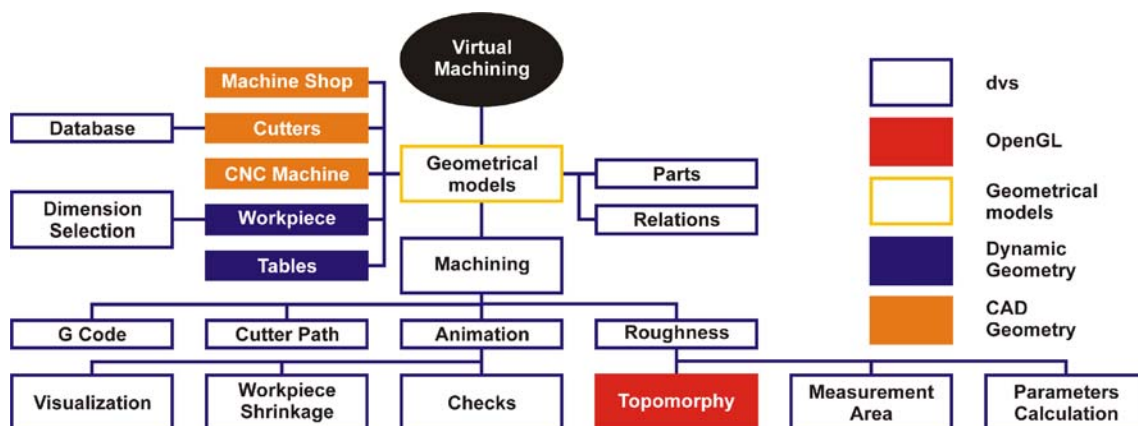


Fig. 1 Structure of the virtual environment for machining processes simulation

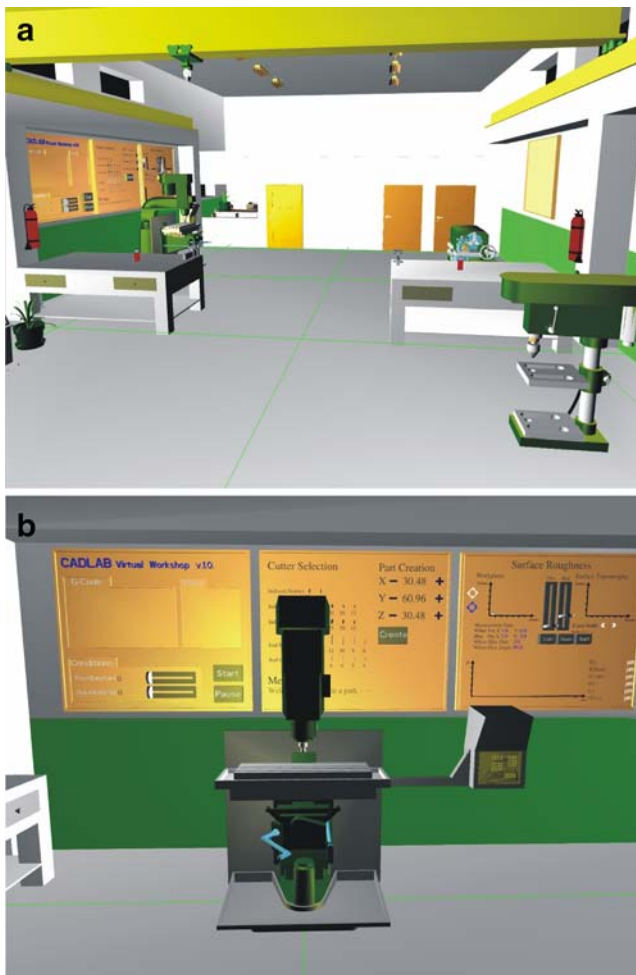
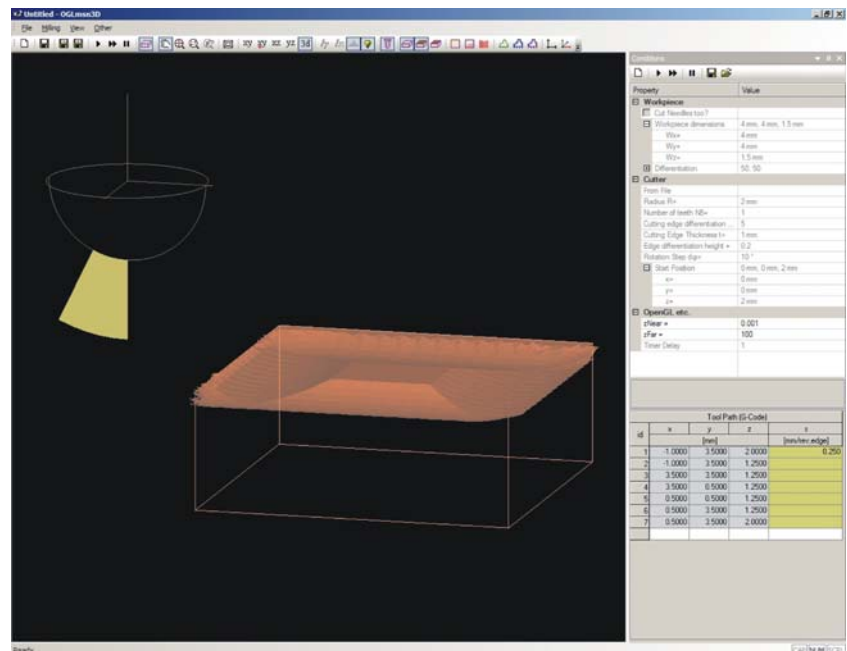


Fig. 2 Virtual environment for machining processes simulation

Fig. 3 OpenGL machining processes simulation environment for machined surface topomorphy determination



roughness parameters and the measurement area topomorphy. Finally, the entire machined surface topomorphy can be visualized as a three dimensional model, that can be inspected from different perspectives.

The virtual environment features and the models employed in its development are described in detail in Bilalis et al. [9]. The current study focuses on the quantitative data capabilities of the system and the process developed for their verification.

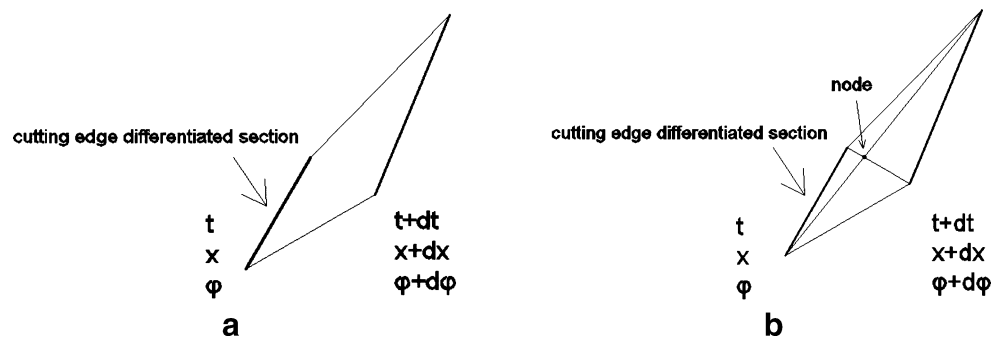
#### 4 Quantitative data determination

A model was developed for surface-roughness quantitative data determination. In the model, parameters such as the cutting speed, rate, depth of cut, cutter diameter, number of teeth and cutting edges geometry that contribute in surface-roughness formation are considered. Parameters that contribute in surface-roughness formation, such as the workpiece and the cutter material, quality and type of the cutter, cutter wear, quality of jigs, fixtures, the use of lubricant, vibrations in the machining process are not considered.

##### 4.1 Determination of machined surface topomorphy

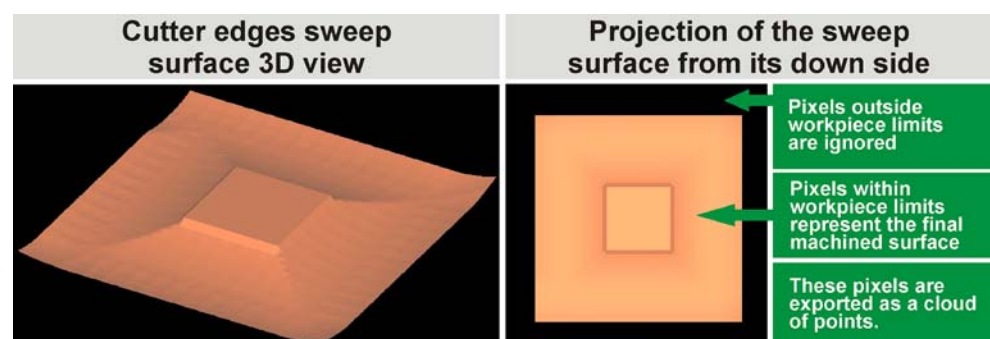
The model for the determination of the machined surface topomorphy was implemented in a three dimensional graphics environment developed in OpenGL (Fig. 3). The simulated motion of the cutter and the cutting conditions are obtained directly from the G code file. The sweep

**Fig. 4** Sweep surface of a differentiated cutting edge segment



surface produced by the cutting edges is being determined, by successively placing the cutter in differentiated path positions, according to the cutting conditions. Cutting edges shape is defined from the outer edge profile of each cutting edge. Each cutting edge is approximated by equal linear segments. For each two adjacent discrete positions of each cutting edge segment a linear surface is defined (Fig. 4a), which is subsequently divided into four triangular surfaces, by adding a node in the “middle” of the surface (Fig. 4b). This is necessary in order to avoid crossed cutting edge segment ends and to convert the linear surface into four flat surfaces. In the sweep surface there are overlapping triangles, since part of each cutting edge sweep is being overlapped by the next cutting edge sweep or the next cutter pass sweep. The final machine surface topomorphy is derived by projecting from the down side the sweep surface produced by the cutter. During this projection the overlapped geometry is not visible, due to the hidden line algorithm that projects to the user only the geometry visible in each point of view. This final machined surface topomorphy is derived from this projection in the form of cloud of points (Fig. 5). The coordinates for the cloud of points are determined. The pixels within workpiece limits visualize the machined surface (Fig. 5). These pixels are converted into X and Y coordinates from their position in the graphics environment. The corresponding Z coordinate is derived from the visualization system Z buffer. The coordinates for the cloud of points describing the machined surface topomorphy is exported in a text file and used to calculate quantitative parameters for the machined surface roughness in the virtual environment.

**Fig. 5** Determination of the final machined surface topomorphy



#### 4.2 Calculation and visualization of surface-roughness parameters in a virtual environment

A table was developed for surface-roughness quantitative data visualization (Fig. 6). On the upper part of the table the measurement plane on the workpiece machined surface is defined. On the lower part of the table the selected measurement plane topomorphy and the respective surface-roughness parameters values are being visualized.

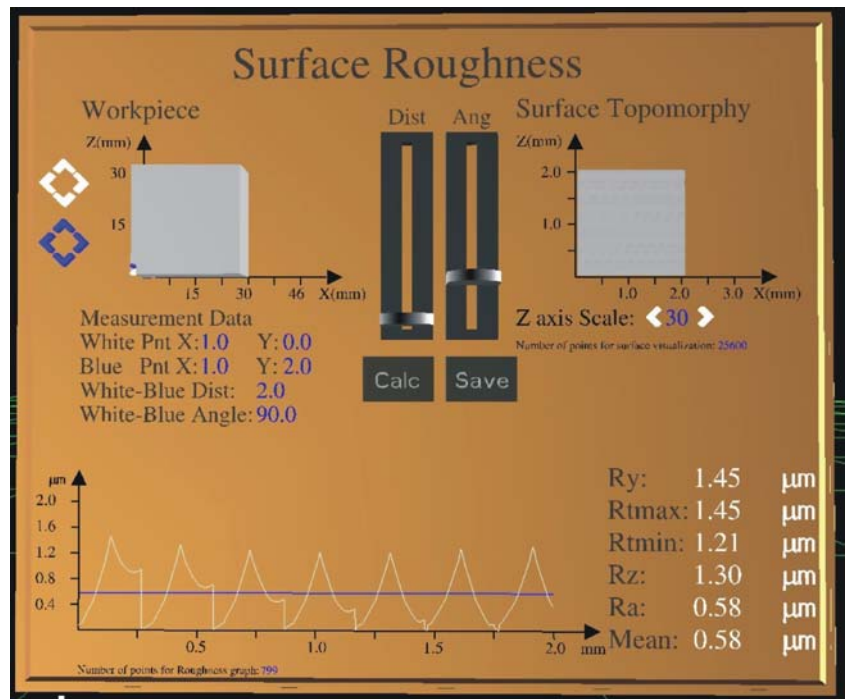
For the determination of the measurement plane, a handler was developed (Fig. 7). The handler defines a plane vertical to the machined surface in which topomorphy will be determined and surface-roughness parameters will be calculated from this topomorphy. The system user defines the position of each handler end and the handler ends define surface roughness measurement plane limits.

For surface-roughness parameters determination, cloud points near the vertical measurement plane are retrieved from the file. The user has the ability to create a machining process report in the form of a text file (Fig. 8). In the machining process report file, surface-roughness data for a region around the measurement plane are being stored and can be acquired for further use. This process can be repeated in any other region of the machined surface.

#### 5 Model verification

In this section the process for the verification of the developed surface-roughness quantitative data determination model is described. The process is shown in Fig. 9.

**Fig. 6** Surface roughness results calculated with the developed model as they are presented in the virtual environment. Up Milling,  $sz=0.2$  mm/rev, edge,  $txy=0.3$  mm,  $tz=0.3$  mm, ball-end cutter D20,  $z=1$ , P02 (TiN), Ck60



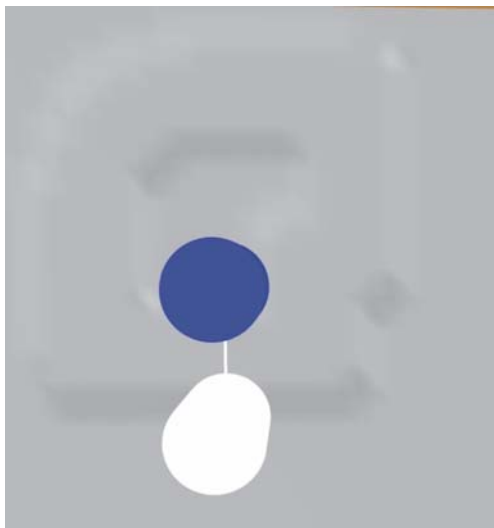
5.1 Verification with the MSN model

The MSN model [2] is used mainly to mathematically verify the machined surface topomorph determined with the presented model. Moreover, surface-roughness parameters values calculated with the MSN model were compared with values calculated with the presented model for identical cutting cases.

For the verification of the machined surface topomorph determination model, the MSN (Milling Simulation by Needles) model was integrated in the developed software.

This model determines the machined surface topomorph and roughness. In the model, the workpiece is modelled with vertical linear segments [2], the so-called “Needles” (Fig. 10). As the cutter moves along the machining process trajectory, the intersection between the cutter edges and the linear segments is determined. Linear segments decrease their height to the lowest intersection position. At the end of the simulation, linear segments vertices define the final machined surface. The model was experimentally verified and the calculated roughness levels were found to be in agreement with the experimental ones.

The MSN milling simulation model is being executed simultaneously with the model developed in the current study. Two different clouds of points are derived, one from the linear segment vertices of the MSN model and another



**Fig. 7** Measurement area determination with the use of the handler

Machining Process Report

Input Data  
G code file: gcode.txt  
Cutter: Ball End with 10mm Diameter and 72  
Workpiece dimensions: 121.92mm X 60.96mm X 121.

Roughness Measurement Report

Angle	Ry	Rtmax	Rtmin	Rz	Ra	Mean
0	1.45	1.45	1.21	1.30	0.58	0.58
10	1.54	1.89	1.37	1.38	1.04	0.76
20	1.50	1.54	1.65	1.43	1.07	0.60
30	1.52	1.86	1.67	1.46	0.86	0.89
40	1.72	1.66	1.49	1.36	0.88	1.00
50	1.72	1.82	1.27	1.65	0.80	0.75
60	1.79	1.76	1.43	1.59	0.71	0.76

**Fig. 8** Machining report example

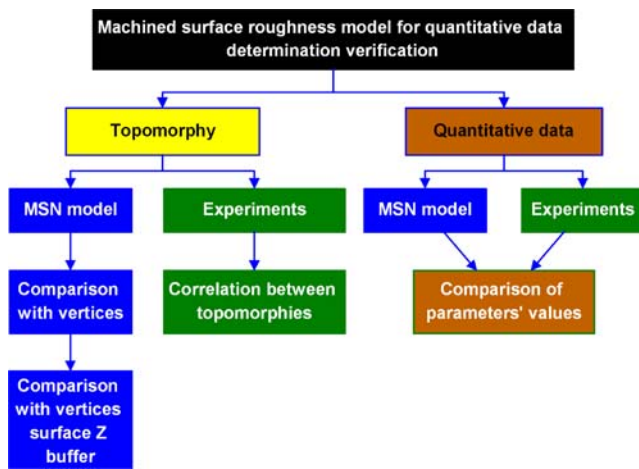


Fig. 9 Quantitative data determination model verification process

from the Z buffer values of the pixels within workpiece limits representing the lowest cutter sweep surface. Since both models are executed simultaneously during the machining process simulation, the two clouds of points are formed with the same cutting conditions. The machined surface determination method and the density of the workpiece discretization are different between the two models. In the MSN model, the density of the workpiece discretization is determined by the number of linear segments used for the workpiece modelling (Fig. 10). In the developed model the workpiece discretization depends on the selected zoom level during the machined surface clouds of points' formation and storage (Fig. 10).

For the verification of the presented model, the two clouds of points are compared. The comparison aims at the determination of the Z buffer accuracy with respect to a mathematical method. Due to different workpiece discretization in the two models, Z coordinates are compared for vertices and pixels, respectively, having similar X and Y coordinates. For the comparison of the two clouds of

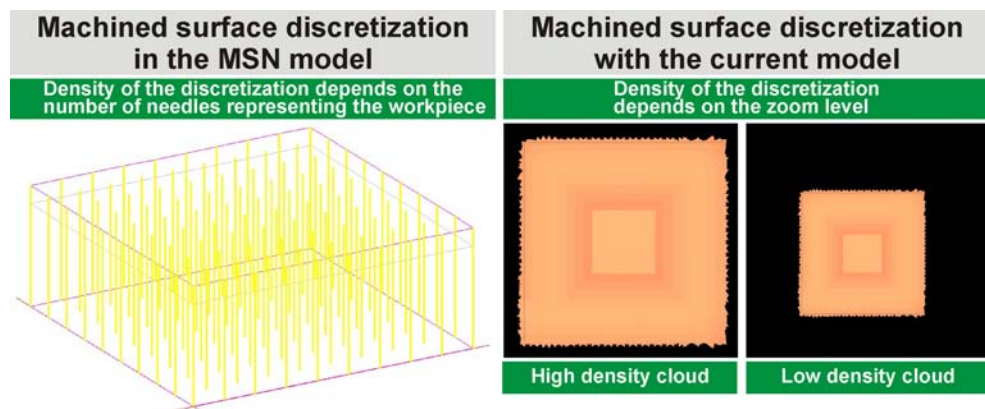
points, first the discretization step in X and Y direction is determined for both clouds. From the discretization step, points with similar X and Y coordinates from both clouds are determined. For these points, the Z coordinate is transformed to the same coordinate system. This is necessary, since linear segment vertices Z coordinates provide the value of workpiece Z dimension at each point, while Z buffer values provide the distance between the respective pixel and the camera. Z coordinates are compared for the respective points. At each workpiece position the difference and the difference percentage are calculated. Finally, the maximum difference and difference percentage in Z direction are calculated for the two clouds of points.

The accuracy of the comparison method depends on the discretization step in the clouds of points, since, as the density of the clouds increases, the compared points are closer and the accuracy of the comparison is higher. A difference in the Z coordinate is expected since the compared points are not in the exact same position.

The second verification determines the accuracy of the cutter sweep surface. For this verification, a surface is defined by the linear segment vertices. This surface is being stored with the same method as the cutter sweep surface that is a cloud of points produced using the Z buffer. This cloud of points is compared with the cutter sweep surface cloud of points by directly comparing the Z coordinate of every pixel. Since both clouds of points in this verification are produced with the same method and at the exact same position and zoom level, the difference between them shows the level of accuracy of the machined surface determined with the current study model.

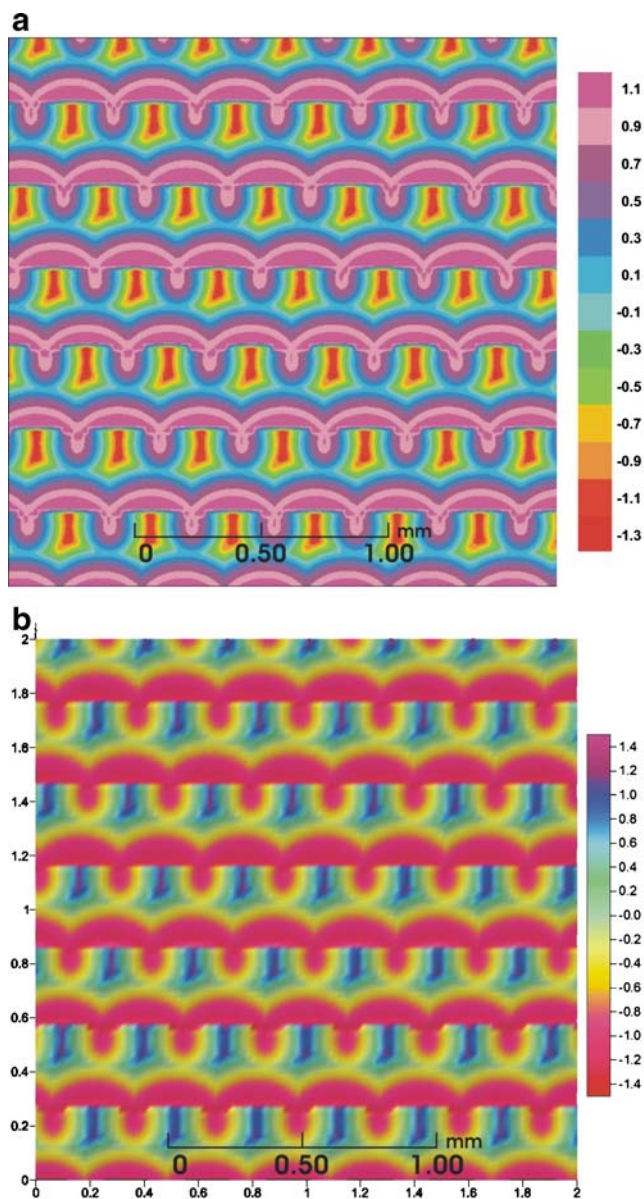
A software tool was developed according to the described comparison methodology for the verification of the presented model results with the MSN numerical model. The average deviation between the linear segments cloud and the cutter sweep surface cloud was 3%. The average deviation between the surface produced with the needles

Fig. 10 Discretization of the machined surface topomorphy



vertices and the cutter sweep surface cloud was 0.05%. In Fig. 11, for the same machining operation, surface topomorphy defined by the MSN model and by the Z buffer is shown in isosurface mode with color scale, to facilitate evaluation.

The MSN model calculates the average value of surface-roughness parameters ( $R_t$ ,  $R_z$ ) for the whole determined topomorphy in each cutting case. These values were correlated with equivalent surface-roughness parameters values calculated with the presented model. The average deviation between these values was 3%.



**Fig. 11** Machined surface topomorphy. Down milling,  $s_z=0.3$  mm/rev, edge,  $t_{xy}=0.3$  mm,  $t_z=0.3$  mm, Ball End D20,  $z=1$ , P02 (TiN), Ck60

## 5.2 Verification with experimental data

Surface roughness results acquired from the system were compared with experimental data to directly verify the developed model. A cutting case was defined. The cutting case part and its production process were designed in a CAD/CAM system. The part was manufactured with a ball-end tool with one cutting edge and different cutting conditions in CNC milling machine using the G code file produced by the CAM system. The G code file used for the part manufacture was imported in the virtual environment for the simulation of the process, in order to ensure that the real and the virtual experiment have identical cutting parameters. The part developed for the cutting case is shown in Fig. 9. The simulation of the machining process for the construction of the part geometry in the virtual environment is shown in Fig. 13. The maximum dimensions of the virtual part shown in Fig. 13 are larger than the maximum dimensions of the part shown in Fig. 12, but that does not affect the constructed geometry in the experiment.

The pocket geometry of the cutting case part was constructed several times with different cutting conditions (up/down milling, change of feed, step over, and depth of cut). To construct the pocket geometry, a circular trajectory was followed in all cases (Fig. 14). The number of passes in each iteration is determined according to the step over parameter value defined in the cutting conditions.

For the verification of the model results, machined surface topomorphy produced by the computational model was compared to the experimental topomorphy. Figure 15 shows a typical correlation performed between the computational and the experimental results for two different cutting conditions. The left image of this figure shows a photograph of the machined surface topomorphy produced in the experiment with P02(TiN) cutter material and CK60 workpiece material. The middle and the right image of the same figure shows the computationally produced surface topomorphy, in two different ways, in iso-surface form and in 3D form. Figure 16 shows a correlation between the computational and the experimental measurement plane profiles. The experimental profile is presented as it was received from the profilometer. The MSN and the current model computational profiles were determined from the developed system. The correlation between the experimental and the computational results exhibits that the topomorphies are in good agreement, considering that there are parameters that could not be taken into account in the developed computational model.

In order to verify the quantitative data the presented model calculates, its results were compared with equivalent data determined in the experiment. For each cutting condition in the experiment, roughness measurements were taken inside the pocket geometry of the part vertically to

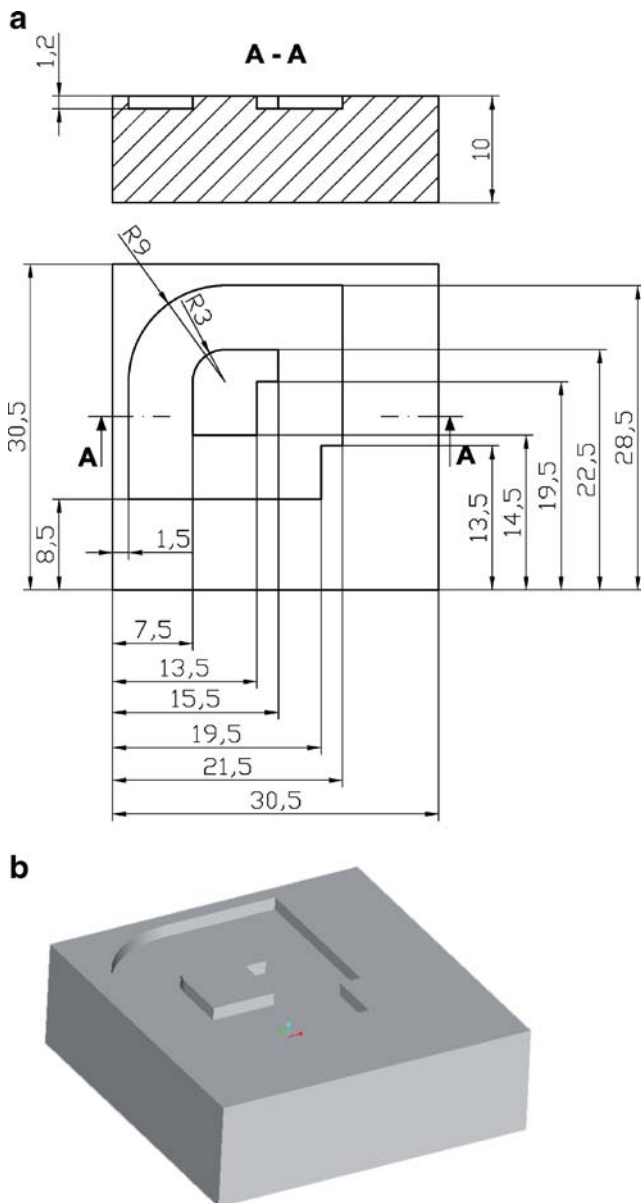


Fig. 12 Machining simulation in the virtual environment

the feed direction, in four different areas in the trajectory. In each area, measurements were taken in measurement planes with length 5 mm (Fig. 14). In Fig. 17, calculated surface-roughness parameters values are compared with the equivalent values measured in the experiment for different cutting conditions. Results from the virtual environment and the experiment are in good agreement, considering that some parameters affecting surface roughness are not taken into account in the developed computational model. As it is shown in the figure, in down-milling, experimental values are closer to the calculated ones. In up-milling, the deviation between the experimental and the calculated values is higher than in down-milling. This is due to the fact that in up-milling there are more vibrations than in

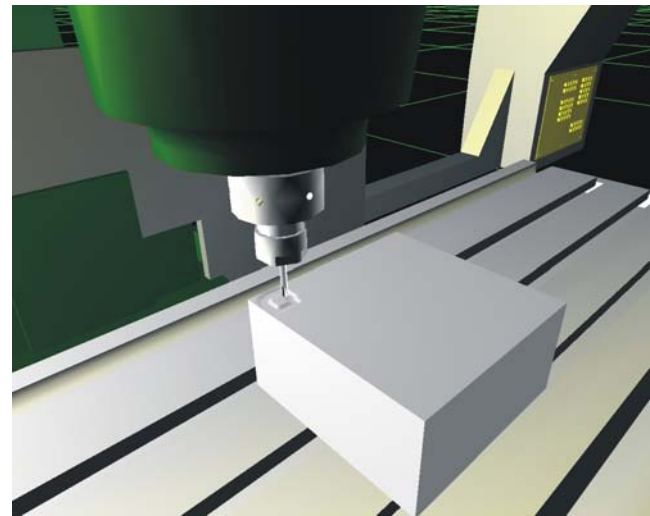


Fig. 13 Experiments' part geometry

down-milling and, since vibrations are not considered in the computational model, the deviation between the experimental and the calculated values in up-milling is higher. There are more vibrations in up-milling than in down-milling, because in down-milling cutting forces act in a direction towards the milling machine table, making the workpiece more stable than in up-milling where cutting forces act in a direction opposite to the milling machine table, as they were trying to lift the workpiece from the table, making it less stable.

## 6 Discussion

In the presented research a model for the determination of quantitative data for machining processes was developed

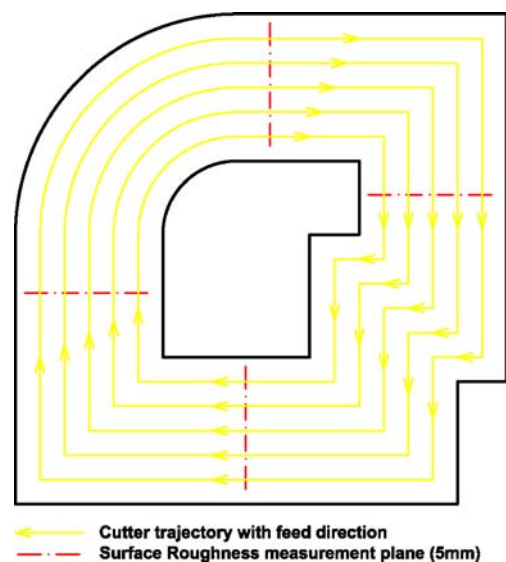
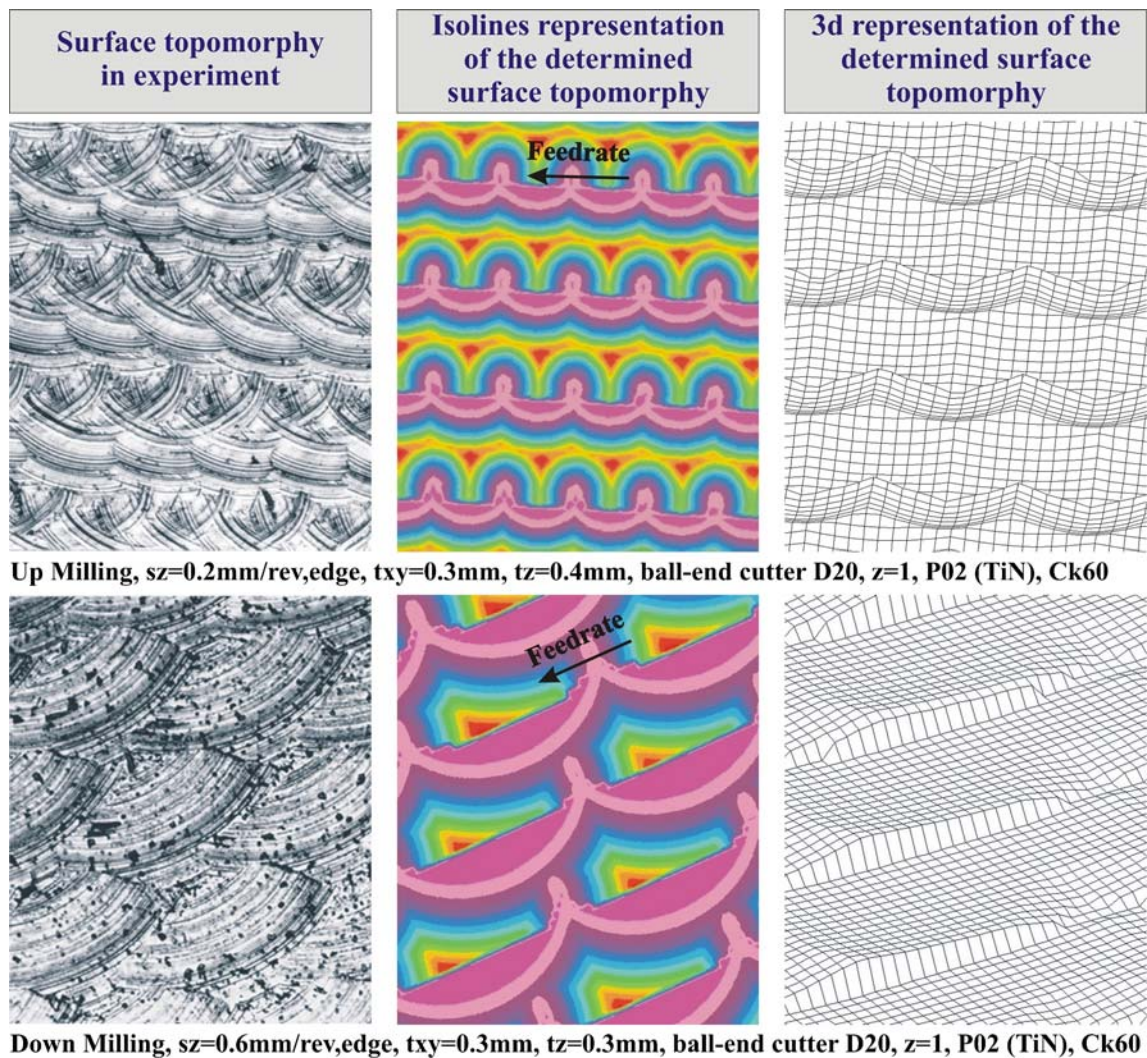


Fig. 14 Pocket milling trajectory and measurement planes





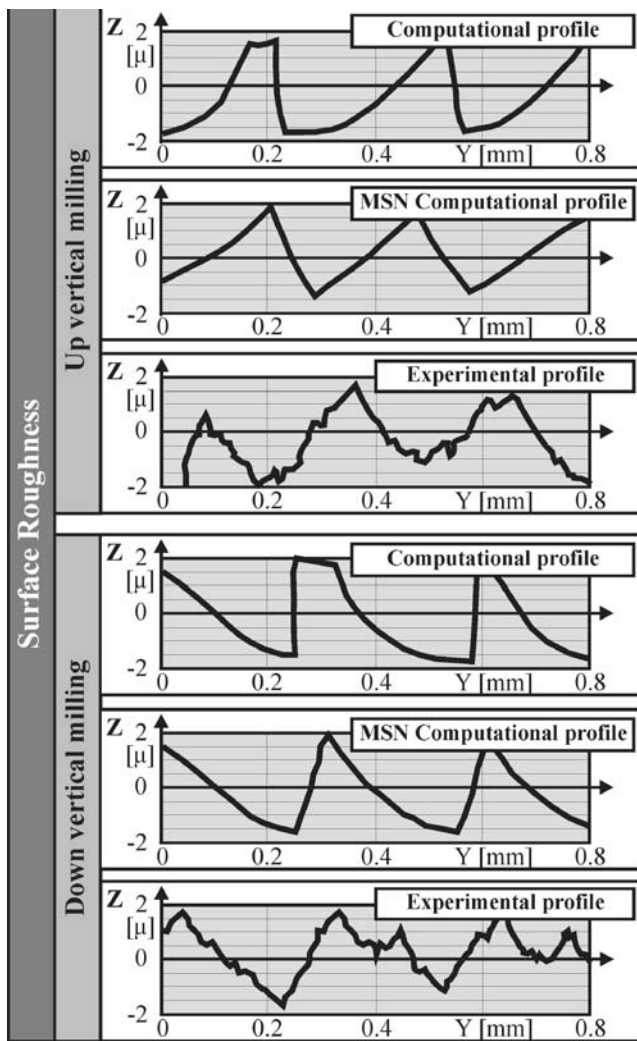
**Fig. 15** Comparison between the experimental and the determined surface topomorphy

and integrated in a virtual machine shop environment, which was also developed from scratch. The system is aiming at the evaluation of the use of virtual environments in production design processes. In this study the process for the verification of the developed model for the determination of quantitative data related to the machined surface roughness is described. According to the verification method followed, the results of the model have adequate accuracy, however some factors related to the verification process and the model need to be further discussed.

The verification processes followed employs an existing numerical model and data from experiments to verify the machined surface topomorphy and roughness parameters values. The simulated machined surface topomorphy is verified with the numerical model. Machined surface topomorphy experimental results were compared with computational results (Fig. 16). Also, a qualitative compar-

ison was implemented (Fig. 15). In order to verify surface-roughness parameters values, computational model values were directly compared with values from the numerical model and experiments for identical cutting conditions. Due to the stochastic nature of the machining processes [10], average values from 20 measurements for both the computational model and the experiment were calculated for the comparison.

Another issue that needs to be discussed is the accuracy of the presented model for surface-roughness determination. The determined machined surface topomorphy is used to calculate surface-roughness parameters values in the model, so the accuracy of the topomorphy directly affects the calculated quantitative data. The accuracy of the developed model for machined surface topomorphy determination is influenced by the cutter model and trajectory discretization density, the hidden lines algorithm employed

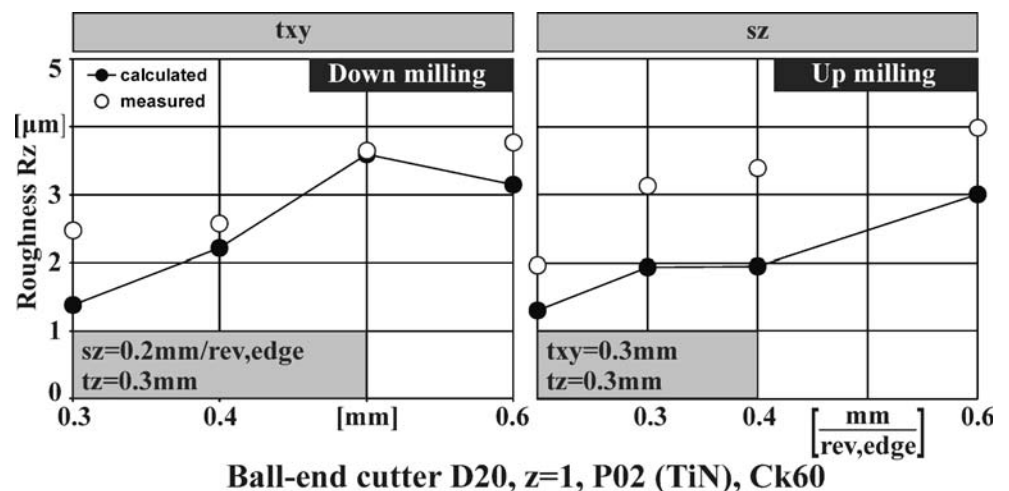


**Ball End D20, z=1, P02 (TiN), Ck60,  $t_z=0.3\text{mm}$ ,  $t_{xy}=0.3\text{mm}$ ,  $s_z=0.6\text{mm/rev,edge}$ ,  $v=45\text{m/min}$**

**Fig. 16** Comparison of the computational and the experimental surface-roughness measurement plane topomorphy

by the system and the projection type used for three-dimensional graphics visualization. Orthographic and perspective projection is supported. Orthographic projection is used because in perspective projection, objects are deformed to create the sense of depth to the user and, since in the developed model data related to every pixel within the workpiece limits are acquired from the graphics card Z buffer, errors can arise during the storage of the machined surface cloud of points, because of the deformed visualization. The projection position and angle also affect the accuracy of the developed model because they influence the Z buffer accuracy. The accuracy of the Z buffer depends on projection parameters like the horizontal and vertical distance between the camera and the surface, the field of view, and the position of the near (znear) and the far (zfar) clipping planes. In OpenGL graphics windows, the geometry visible at each camera position is the geometry that lies between the znear and zfar clipping planes. The position of these planes is defined relative to the camera and according to each application's requirements. Better Z buffer accuracy is achieved when znear plane is not close to the camera, objects are close to the znear plane and the distance between the znear and the zfar plane is small [11, 12]. Z buffer is employed in the presented model for the determination of the machined surface triangles vertices coordinates, so it is critical to acquire the most accurate data from Z buffer, in order to determine more accurate surface-roughness parameters values. Several executions of the model has shown that, when each of these parameters is in a certain range of values, the difference in the cloud points coordinates is negligible, so a set of values was selected for all machining simulations. Finally, machined surface topomorphy accuracy is influenced by the density of the cloud of points. To overcome screen pixel resolution limitations, the machined surface is zoomed on the screen in the measurement area, which usually has 5 mm of length as in real surface-

**Fig. 17** Comparison of the calculated surface-roughness parameters values with the equivalent values measured in the experiment



roughness measurements. The cloud of points is produced for this zoomed view, which means that for 1280x1024 screen resolution a cloud with almost 700,000 points for the measurement area is produced. A cloud of points is produced in this way for each measurement area.

## 7 Conclusions

This research presents a virtual environment for machining processes simulation in order to evaluate the use of the technology in production design processes. The evaluation is expected to contribute in the extraction of critical conclusions for the employment of the technology in real industrial environments, aiming at the comprehension of the affect of the cutter geometry and the cutting conditions on the produced machined surface topomorphy. This information contributes to the conception of the influence of the machining process parameters in the resulting surface quality and it can facilitate the selection of the most appropriate cutting parameters for each application. The developed system extends CAM system capabilities, since it provides higher level visualization functionalities and quantitative data for the production process defined in the CAM system. A new method based on OpenGL programming language is presented for machined surface topomorphy determination in order to calculate critical quantitative data affecting machined surface roughness. This graphical method is integrated in the virtual environment and a methodology for presenting its results is demonstrated. Similar methods can be applied in order to obtain the results from the simulation of the manufacturing processes and also to present the results to the user.

The current study focuses on the process for the verification of the developed quantitative data determination model. Although the verification method followed does not completely confront the stochastic behavior of machining processes, it showed that the results acquired by the system

are in agreement with both the employed numerical model and the experimental results, making the model suitable for integration in production design processes.

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