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Prediction of Surface Topomorphy and Roughness in Ball-End Milling

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Milling is today the most effective, productive and flexible-manufacturing method for machining complicated or sculptured surfaces. Ball-end tools are used for machining 3D freeform surfaces for dies, moulds, and various parts, such as aerospace components, etc. Milling data, such as surface topomorphy, surface roughness, non-deformed chip dimensions, cutting force components and dynamic cutting behaviour, are very helpful, especially if they can be accurately produced by means of a simulation program. This paper presents a novel simulation model, the so-called MSN-Milling Software Needle program, which is able to determine the surface produced and the resulting surface roughness, for ball-end milling. The model simulates precisely the tool kinematics and considers the effect of the cutting geometry on the resulting roughness. The accuracy of the simulation model has been thoroughly verified, with the aid of a wide variety of cutting experiments. Many roughness measurements were carried out on workpieces, which were cut using a 5-axis machining centre. The calculated roughness levels were found to be in agreement with the experimental ones. The proposed model has proved to be suitable for determining optimal cutting conditions, when finishing complex surfaces. The software can be easily integrated into various CAD-CAM systems.

Keywords: Cutting; Surface roughness; Surface topomorphy

1. Introduction

The industrial significance of software able to simulate and visualise manufacturing processes is now clear. More specifically, in milling processes, the advanced capabilities of modern CNC machine tools need to be supported by simulation models, able to optimise the cutting parameters involved computationally.

Milling, using ball-end tools is extensively used for the finishing processes for freeform surfaces. The topomorphy of the resulting surface is a challenging subject and various simulation models have been proposed for determining it [1–6]. These models aim at determining the penetrations of the cutting tool in the workpiece, and calculating the dimension of the chips produced, and the resulting cutting forces and the final topomorphy of the part [7–12].

The quality of the surface produced by milling depends on various technological parameters, such as the cutting conditions, the cutting tool and the workpiece specification, but it also depends on the selection of the cutting strategy. The applied milling strategy derives from the relative position of the cutting tool and the workpiece, as well as the kinematics of the cutting tool during the operation. The basic parameters, which influence the cutting geometry, are the axial (t_Z) and the radial (t_{XY}) depth of cut and the feedrate (s_Z) of the cutting tool.

This paper presents an analytical model, which describes the geometry of the milling process using various tools and has been applied for ball-end tools. The model determines quantitatively the topomorphy of the surface produced and the resulting surface roughness. The description of cutting the part is based on the analysis of the workpiece in a number of finite linear segments, the so-called needles. The model is used to calculate the influence of various cutting parameters in the resulting surface roughness and its results have been experimentally evaluated through cutting experiments. The software can also be used to determine the optimal cutting conditions in multi-axis milling.

2. The Milling Software Needle (MSN) Program

The MSN algorithm has been developed as a modular and open architecture. The algorithm is supported by a powerful

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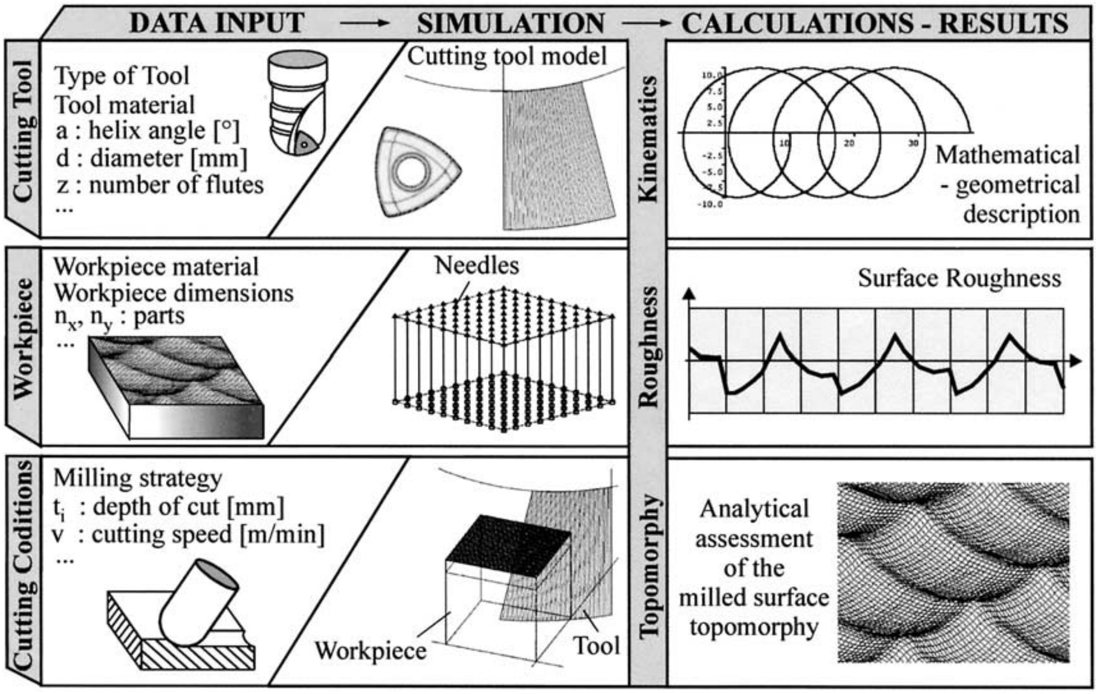

Fig. 1. Data input and typical results from the MSN model.

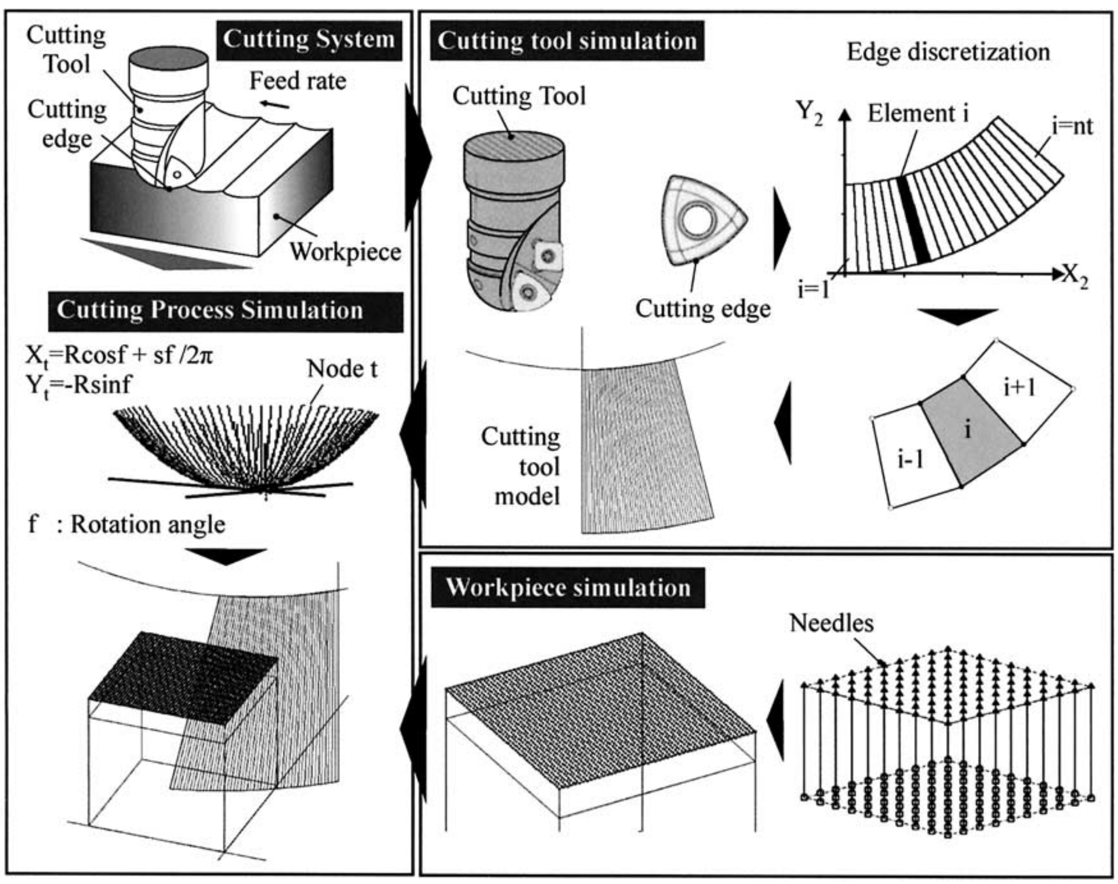

Fig. 2. Simulation principles for the kinematics and the simulation of the cutting tool and the workpiece, respectively.

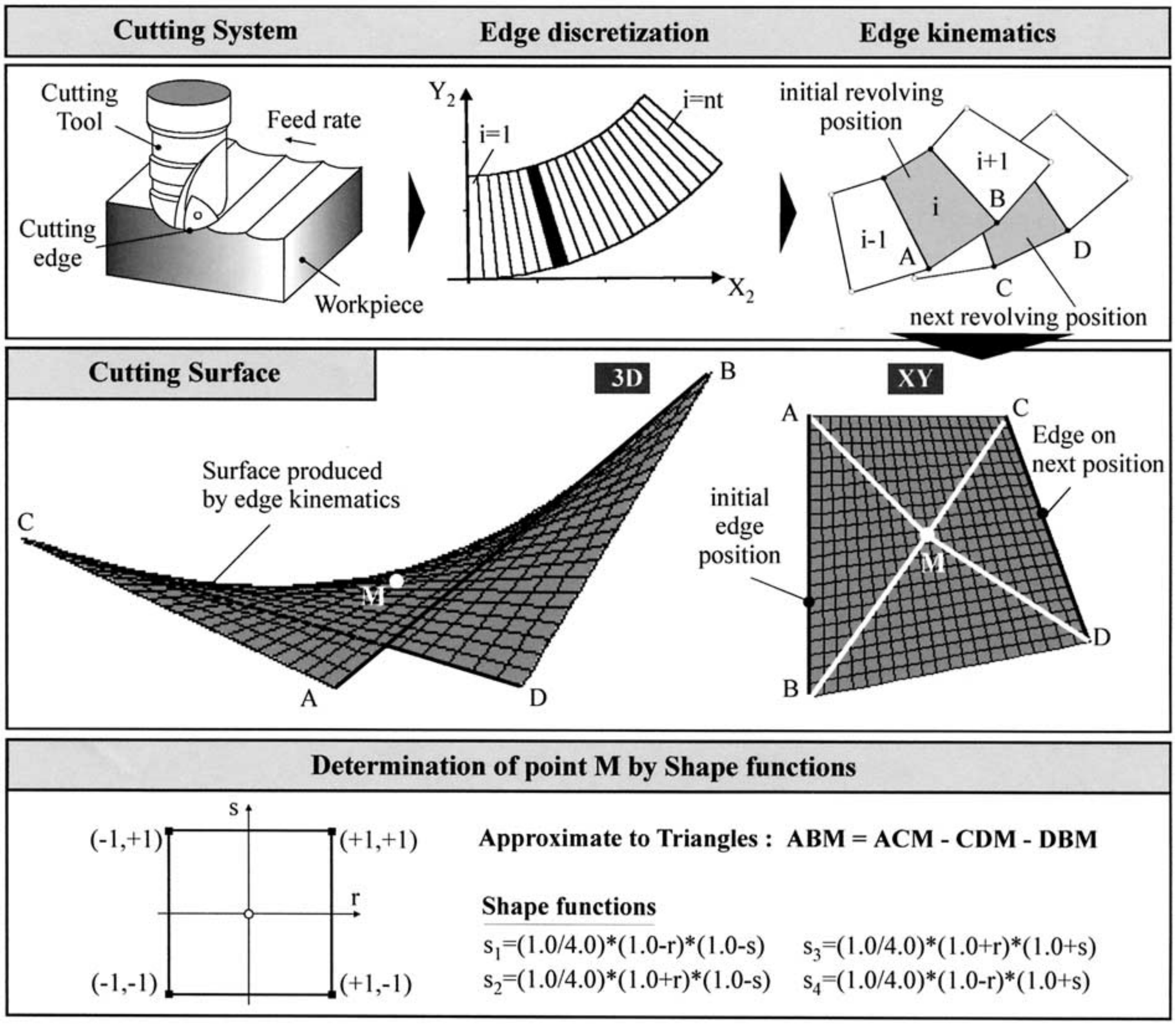

Fig. 3. Simulation of the tool penetrations into the workpiece with the aid of parametric shape functions.

graphical user interface, which optionally offers animated clips of the cutting process. The operating principle of the software is presented in Fig. 1. Taking into account that multi-axis milling is a cutting process depending on many parameters, the data input includes every possibly parameter involved. Data input includes the geometrical and technological features of the cutting tool, the material and the geometry of the workpiece, and the cutting conditions, such as the feedrate, the cutting speed, and other parameters.

The algorithm processes the aforementioned data, enabling a mathematical–geometrical description of each specific cutting case to be made. Significant technological quantitative outcomes of the algorithm are the resulting surface topomorphy and roughness. In addition to these results, the model is capable of determining chip cross-sections and cutting force components, in any desired position. This type of result is very useful in dynamic and strength calculations, but they are not analytically presented in the present paper.

The initial tasks of the simulation model are illustrated in Fig. 2. The cutting system, tool workpiece arrangement, is computationally analysed, in order to produce cutting process simulation models of the cutting edge and of the active section of the workpiece. This task is based on a variety of coordinate systems and on special transformation functions. More specifically, for the cutting-tool simulation, the cutting edge is decomposed in *nt* elementary cutting edges of trapezoid shape. Similarly, the workpiece simulation is done with the aid of linear segments, the so-called needles. It is reasonable to compare the simulation model of the workpiece with a brush. The accuracy of the simulation depends on the density of the discrete parts of the tool and of the workpiece, respectively. However, there is a specific upper limit to the density beyond which the density does not have any impact on the precision of the simulation model, and this limit prevents the software from wasting CPU resources.

Using the appropriate analytical process, the geometrical model of the cutting tool follows the kinematics of the selected

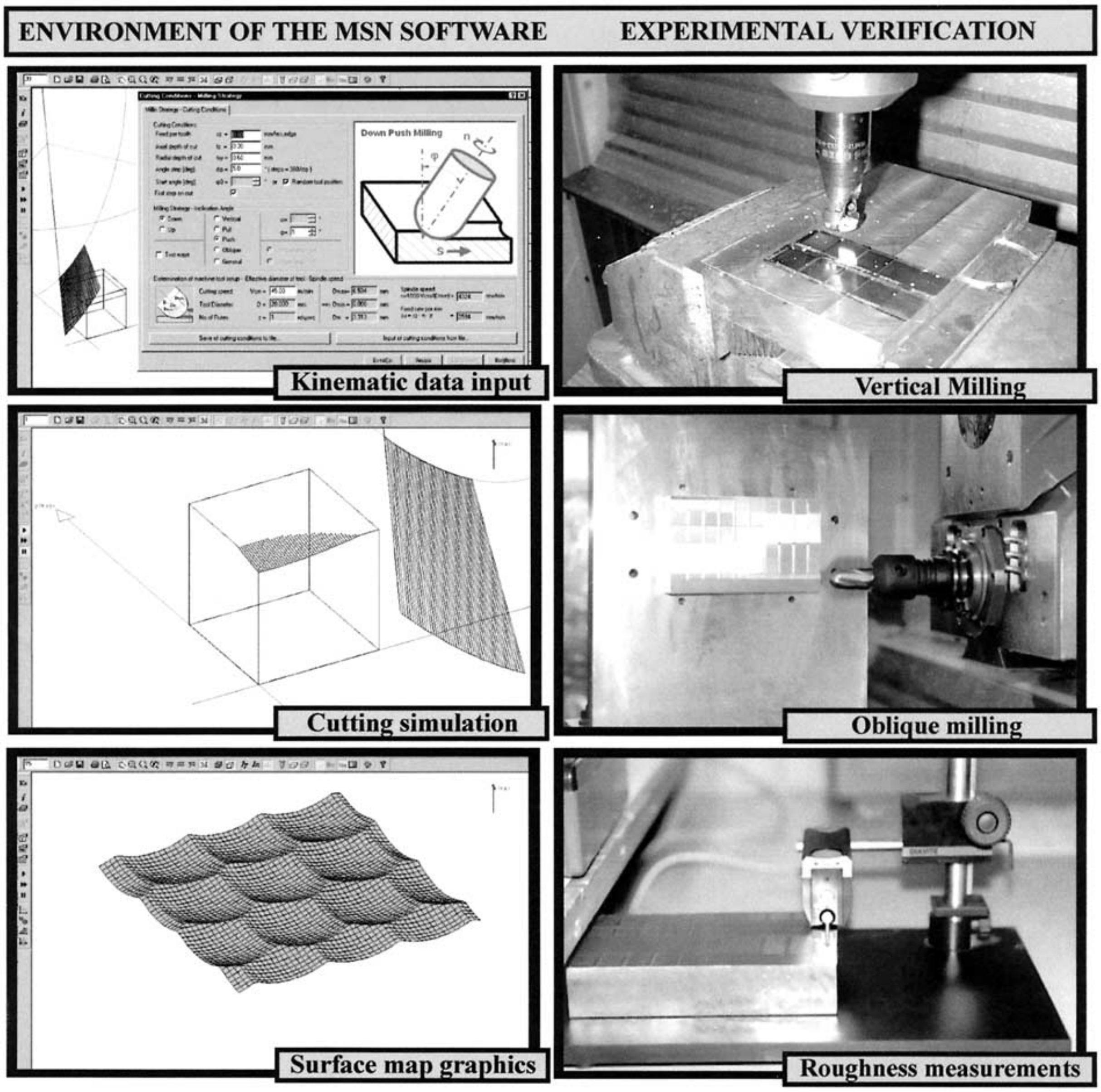

Fig. 4. Snapshots from the environment of the model and of the experimental verification process.

milling operation and intersects segments of the needles, forming the workpiece. This process is schematically presented in Fig. 3. In order to enhance the computational performance, the so-called shape function advanced mathematical tools, are implemented in the MSN program. The reason is that the cutting surface generated by each segment of the cutting edge has a complex shape, as the edge is simultaneously rotating and moving along the direction of the applied cutting feed. The cutting-edge surface is oriented parametrically. The point *M* belongs to the askew surface *ABCD*, and it is described computationally by the shape functions at the bottom part of Fig. 3. However, segments *AM*, *BM*, *CM*, and *DM* do not fit in this surface, owing to the approximation method. Each of the triangles *ABM*, *ACM*, *CDM* and *DBM* define a plane. These planes approximate dynamically to the current orientation of the specific segment of the cutting trace *ABCD*. After the formation of coordination systems at these triangles, the intersections of the needles with these finite planes are determined. The needles trimmed by these four planes form the elementary chip, produced by the specific cutting-edge segment at the specific cutting position. The decision for cutting or not cutting a needle, from each elementary motion of the cutting tool is taken dynamically for a certain area of the processed part, in order to save computing time. At the end of the

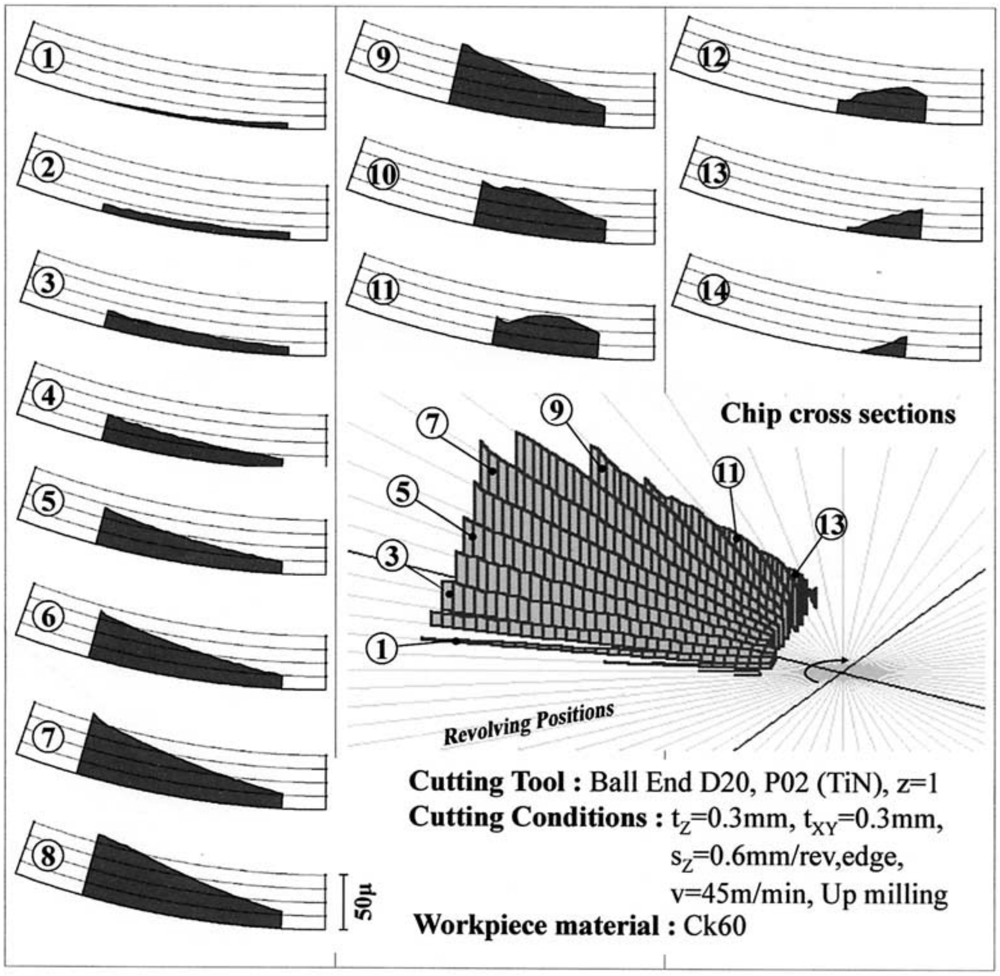

Fig. 5. Calculated undeformed chip cross-sections in ball-end milling.

operation, the milled part consists of a set of reduced length needles, which describe the milled surface, and is able to describe the surface roughness at any desired direction.

The MSN model was developed in the object oriented C^{++} language. The environment is fully parametric and customisable, as it is built with an open and modular structure. Figure 4 illustrates typical windows extracted from the model. In the upper left part of this figure, the kinematic data input form is presented. Each menu has special graphics that visually describe the selectable parameters. It has to be noted here that the data input forms include every possible parameter and specification, extending the applicability of the software. The middle lefthand part of Fig. 4 shows a snapshot of the visual simulation of the cutting process, using a ball-end tool, with one cutting edge. The surface map graphics, in the bottom lefthand part of the same figure, illustrate the surface produced for the specific manufacturing case. The results obtained from the model presented in this paper, correspond to milling experiments, carried out with the aid of a 5-axis machining centre, shown in action in the righthand part of Fig. 4, for two different milling cases: vertical milling and oblique milling. Roughness measurement is also shown. The experimental results, besides their aim to validate the MSN model during its development and optimisation, were necessary to correlate the parameters, which could not be considered during a geometrical simulation.

A significant option in the MSN model is its ability to calculate the non-deformed chips produced, at any position of interest of the cutting tool. Such results for a specific cutting position are shown in Fig. 5. The chip drawn in this figure corresponds to a ball end tool with one cutting edge, cutting at a position with full cutting depth. In this case, the current cutting position is divided into 72 revolving positions, i.e. each revolving position corresponds to a tool rotation of 5°. The program optionally presents a full cutting position or each revolving position individually. The determination of the undeformed chip cross-sections is essential for estimating the cutting force components, which are required for stress or dynamic calculation. This possibility is also included in the MSN model, since it has implemented cutting force components coefficients for a wide variety of tool–workpiece systems.

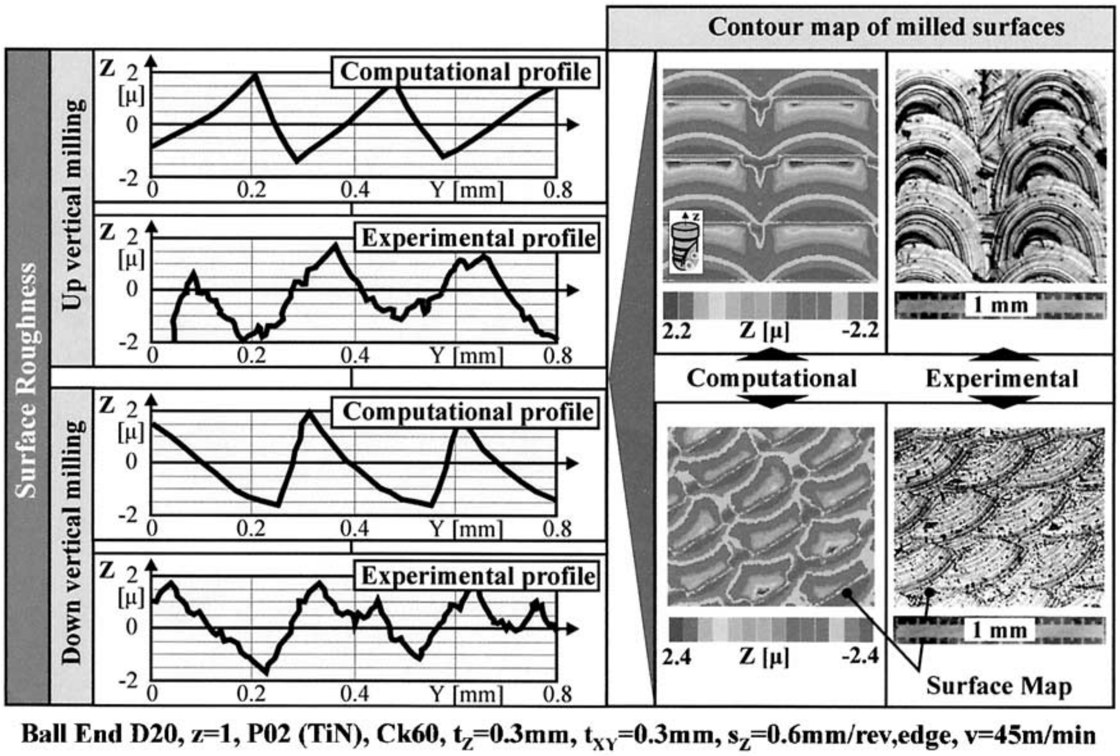

Fig. 6. Comparison between analytical and experimental results for up-vertical and down-vertical milling.

3. Analytical and Experimental Surface Results

The MSN model was used to simulate milling operations, applying identical technological and cutting conditions. Figure 6 shows a typical correlation performed between the computational and the experimental results. The specific cutting case is presented for a typical milling with a ball-end tool with one coated cemented carbide edge, at low cutting speed. The upper part of this figure shows the computationally produced surface, in two different ways, i.e. a 3D form and an iso-surface form. The middle part of the same figure, exhibits the mathematical and the experimental profiles, which are in a good agreement, considering that there are parameters that could not be taken into account by the mathematical simulation. A comparison between the analytical and the experimental profiles is presented in the bottom part of Fig. 6, where the corresponding surface maps are put side by side. The correlation between these illustrations is evident.

An analysis describing the effect of various cutting parameters on the surface roughness was performed. Figure 7 exhibits the influence of the applied cutting feed derived analytically and experimentally. The analysis refers to two different variations of the cutting strategy, i.e. down and up milling, respectively, keeping every other cutting parameter unchanged. The well-known experience of increased roughness versus the level of the cutting feed is presented in this figure computationally and experimentally. For each of the cases examined, the calculated roughness matches the measured one. The same figure illustrates typical micrographs of the surfaces produced for various cutting cases. In the cases examined the cutting tool is placed vertically with respect to the workpiece, i.e. the inclination angles are set to zero.

4. Conclusions

In this paper, a new precise computational approach for simulating multi-axis milling was presented. The MSN model was developed and verified as a powerful tool, able to calculate significant technological data involved in milling operations. The developed algorithm was validated my means of an experimental procedure, using a 5-axis machining centre. The algorithm controls most of the parameters, so that it is able to visualise every kind of milling strategy. The program was applied in this paper, in order to produce surface roughness data, which adequately matches measurements on milled specimens. The algorithm implements subprograms, which are able to determine the chips produced in transient or stable cutting conditions. This kind of information is essential for estimating the cutting force components acting on the cutting tools or on the machine tools. Besides these capabilities, the MSN model contains extended databases of experimentally derived technological parameters, which will be presented in future papers. The software can be integrated into CAD-CAM systems, extending the industrial merit of the program. Considerable

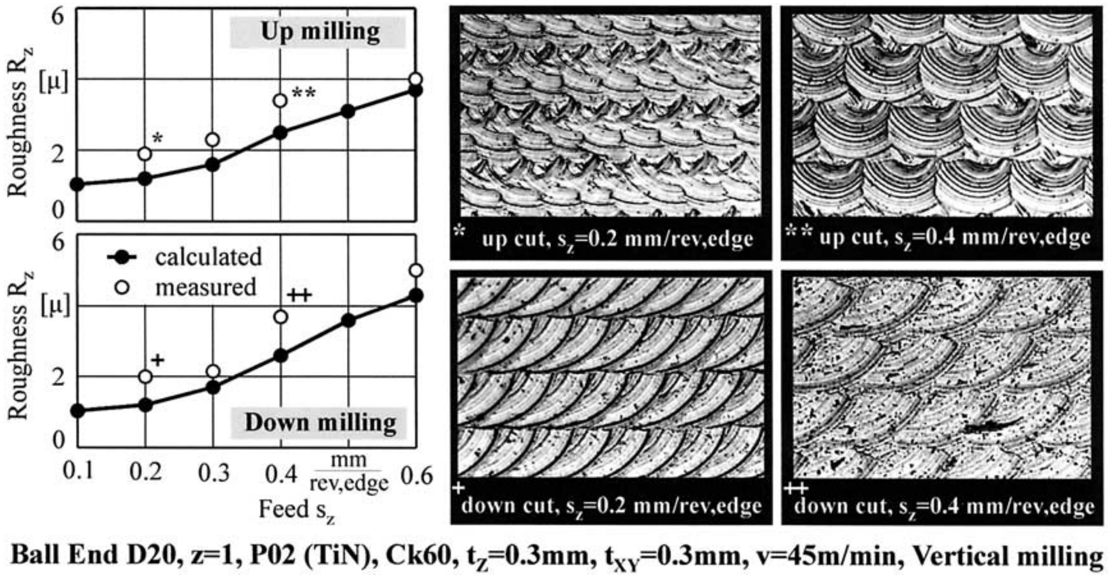

Fig. 7. The influence of the applied cutting feed on the computational and the measured roughness for two different milling kinematics.

attention was paid to the visual representation, in real-time, of the cutting process, especially for educational purposes.

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