Simulating Milled Surface Topomorphy by MSN Software

A. Antoniadis, C. Savakis, N. Vidakis, D. Dogas

Technological Educational Institute of Crete, Heraclion, Crete, Greece

Abstract
CNC milling has become one of the most competent, productive and flexible manufacturing methods, for complicated or sculptured surfaces. In order to design, optimize, built and exploit efficiently modern, up to sophisticated, multi-axis milling centers, their expected manufacturing output is at least beneficial. Therefore data, such as the surface topomorphy, roughness, non-deformed chip dimensions, cutting force components and dynamic cutting behaviour are very helpful, especially when they are computationally produced, by means of simulating software. This paper presents a novel simulation program, the so-called MSN code, which is able to determine the produced surface and the resulting surface roughness, for every possible milling strategy and cutting tool. The model simulates precisely the tool kinematics, considers the effect of the cutting geometry on the resulted roughness and takes into account the tool contact angle, with respect to the feed direction. The completeness of the simulating software has been thoroughly verified, with the aid of a wide variation of cutting experiments. Hereby, several roughness measurements were carried out on workpieces, which had been cut using a 5-axes Milling Center. The predicted roughness levels were found to be in a reasonable agreement with the experimental ones. In a step forward, the proposed model was proved suitable to determine optimal cutting conditions, when finishing complex surfaces. The software may easily be integrated into various CAD-CAM systems.

Introduction
The industrial significance of software able to simulate and visualize manufacturing methods is nowadays implicit. More specifically in milling processes, the advanced capabilities of modern CNC machine tools, must be supported by simulating models able to computationally optimize the involved cutting parameters. Such software tools are extensively applied during the evolution and the exploitation of machine tools.

Milling, especially by ball end tools is broadly used for finishing processes of complex surfaces. The topomorphy of the resulting surface is a challenging research subject and various simulating models have been proposed for determining it [1,2,3,4,5,6]. These models aim to determine the penetration of the cutting tool into the workpiece, and to calculate the dimension of the produced chips, the resulting cutting forces and the final topomorphy of the part [7,8].

The quality of the surface produced by milling, depends on various technological parameters, such as the cutting conditions, the cutting tool and the workpiece specifications, but also on the selection of the cutting geometry. The applied milling strategy derives from the relative position between the cutting tool and the workpiece as well as from the kinematics of the cutting tool during the operation. The basic parameters, which influence the cutting geometry, are the axial and the radial depth of cut and the feed rate of the cutting tool and also the angle of the tool against the processed surface.

This paper releases an analytical model describing the geometry of the milling process with various tools, applied for presentation purposes in ball end tools. The model determines quantitatively the topomorphy of the produced surface and the resulting surface roughness. The cutting part description is based on an analysis of the workpiece in a number of finite linear segments, the so-called needles. The model accounts for tool orientation with respect to the workpiece, offering the possibility to alter tool inclination angles. On the other hand, it can support alternative processing strategies, resulting from these contact angles. Herewith, the model is utilized to calculate the influence of various cutting parameters in the resulting surface roughness. In addition, the specific software may be used to determine optimal cutting conditions in multi-axis milling, in which it has been experimentally evaluated through cutting experiments.
**The Milling Software Needle (MSN Code)**

The MSN algorithm was developed in a modular and open architecture. The algorithm is supported by a powerful graphical user interface, which optionally offers animated clips the cutting process. This feature sets the MSN code fitting to academic purposes, besides its research merit. The operating principle of the software is presented in figure 1. Taking into account that multi axis milling is a multi-parametric cutting process, the data input includes every possibly involved parameter. The input refers to the geometrical and technological features of the cutting tool, the material and the geometry of the workpiece, as well as cutting conditions, such as the milling strategy, the feedrate the cutting speed and other parameters.

<table>
<thead>
<tr>
<th>Data input</th>
<th>Calculations</th>
<th>Output - Results</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of Tool - Tool material</strong>&lt;br&gt;d : diameter [mm]&lt;br&gt;a : helix angle [*]&lt;br&gt;z : number of flutes</td>
<td>Mathematical - geometrical description of the milling kinematics</td>
<td>Overall analytical assessment and process of the milled surface topomorphy</td>
</tr>
<tr>
<td><strong>Workpiece material</strong></td>
<td>Calculation of the undeformed chip cross sections over the development of the cutting edge</td>
<td></td>
</tr>
<tr>
<td><strong>Workpiece dimensions</strong>&lt;br&gt;n, n : parts</td>
<td>Determination of the resulted surface roughness</td>
<td></td>
</tr>
<tr>
<td><strong>Milling strategy</strong>&lt;br&gt;a : depth of cut [mm]&lt;br&gt;v : cutting speed [m/min]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Fig.1. The structure of the MSN milling simulating software.](image)

The algorithm processes the aforementioned data, enabling the mathematical-geometrical description of each specific cutting case. Significant technological outcomes of the algorithm are the resulting surface topomorphy and roughness, quantitatively. Besides such results, the model is capable to determine chip cross-sections and cutting force components, in any desirable position. Data of this kind are very useful in dynamic and strength calculations, although they are not analytically presented in the present manuscript.

The initial tasks of the simulation algorithm are illustrated in Fig. 2. The tool-workpiece arrangement is computationally analyzed, to prepare the simulating models of the cutting edge and of the active section of the workpiece. This task is based on a variety of coordination systems and on special transformation functions. More specifically, the cutting edge is decomposed into (nt) elementary cutting edges, holding a trapezoid shape. This step is presented in the upper right part of Fig. 2. Similarly, the workpiece is simulated with linear segments, the so-called needles. It is reasonable to compare the simulating model of the workpiece with a brush. The workpiece modeling process is illustrated in the bottom part of Fig. 2. 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 limit below which any further density does not impact on the precision. 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 milling operation and intersects segments of the needles, forming the workpiece. This process is schematically presented in figure 3. In order to enhance the computational performance, advanced mathematical tools, the so-called shape functions are implemented into the MSN code. The reason is that the surface of each segment of the cutting edge has a complex formation, bearing in mind that 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 skew surface ABCD, as it is computationally described by the shape functions of the bottom part of figure 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 dynamically simulate the current orientation of the specific segment of the cutting trace ABCD. In a step forward, and after the formation of coordination systems at these triangles, the intersections of the needles with these finite planes are determined. The cropped needles 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 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 operation the milled part consist of a needles set with reduced length, which describe the milled surface, able to offer the surface roughness at any desired direction.
The MSN software was developed in object oriented C++ language. The environment is fully parametric and customisable, whereas it is built in an open and modular structure. Figure 4 illustrates typical windows of the code. 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 mentioned here, that the data input forms, include every possible parameter and specification, creating in this way general applicable software. The bottom left part of figure 4 exhibits a still of the visual simulation of the cutting process, using a ball end tool, with one cutting edge. Moreover, the upper right part of the same figure, illustrates the produced surface for the specific manufacturing case. The computational data presented in this paper, correspond to milling experiments, carried out with the aid of a 5-axis DECKEL-MACHO machining center, as it is shown in action in the bottom right part of figure 4. The experimental results, besides their aim to validate the MSN software during its development and optimisation process, were necessary to correlate parameters, which are not able to be considered during a geometrical simulation.
A very significant option of the MSN code is the ability to calculate the produced non-deformed chips, at any interesting position of the cutting tool. Such results for a specific cutting position are illustrated in figure 5. The chip inserted 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 separated in 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 chip cross sections is essential to pre-estimate the cutting force components, which are required for stress or dynamic calculation. This possibility is also included to the MSN programme, since it has implemented cutting force components coefficients for a wide variety of tool-workpiece systems.

**Analytical and Experimental Surface Results**

The MSN software was enabled to simulate milling operations, applying identical technological and cutting conditions. Figure 6 shows a typical correlation between the computational and the experimental results. In the specific cutting case, a typical milling case with ball end tool with one, coated cemented carbide edge at low cutting speed is presented. The upper part of this figure illustrates the computationally produced surface, in two different possibilities, i.e. a 3-D form and an iso-surface one. The middle part of the same figure, exhibits the mathematical and the experimental profiles respectively, which are in a good agreement, remembering parameters that could not taken into account by the mathematical simulation. Moreover, a very characteristic comparison between the analytical and the experimental profiles is presented in the bottom part of figure 6, where the corresponding surface maps are put side by side. The correlation between these illustrations is evident.
In a step forward, a parametric analysis describing the effect of various cutting parameters on the surface roughness was performed. Figure 7, exhibits the influence of the applied cutting feed on the produced affinity, as it was derived analytically and experimentally. The parametric analysis refers to two different variations of the cutting strategy, i.e. down and up milling respectively, keeping every other cutting parameter stable. The well-known experience of increased roughness versus the level of the cutting feed is presented in this figure either computationally or experimentally. For each of the examined cases the calculated roughness fit to the measured one. The same figure illustrates typical micrographs of the produced surfaces for various cutting cases. In the examined cases the cutting tool is placed vertically to the workpiece, i.e. the inclination angles are set to zero.
Finally, various cutting strategies, all of them able to be simulated by the MSN code were examined, concerning their effect on the produced surface roughness. Figure 8 illustrates the possible milling strategies, which can be selected by altering the tool orientation and the feed direction. These variations may be met individually or combined in multi axis milling, and are options of modern CAD-CAM systems. Each of them has different roughness expectations, and remembering that this technological parameter is of great importance especially in finishing processes, their quantitative analysis is considerably important. The examination of these cases can be carried out for various tool geometries, whereas in the specific analysis ball end tools were selected.
Figure 7 illustrates the level of the calculated and the measured roughness for various cutting strategies versus the adjustment of the tool inclination angle. As it can be easily observed, the cutting strategy has a significant impact on the expected roughness, whereas the same occurs for the level of the inclination angle. The most attractive method, regarding the surface quality was found to be the up push milling either computationally or experimentally. On the other hand, the less efficient strategy regarding this aspect is the two ways down/push-up/pull milling. This variation of the expected surface quality sets the milling process exceptionally able to be optimised.
Fig. 8. The possible variations of the milling strategies that MSN software can simulate.

Conclusions
In this paper a new precise computational approach to simulate multi axis milling was presented. The MSN software 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 reliable 5-Axis machining center. The algorithm is built in terms of parameters, so that it is able to visualize every kind of milling strategy. The program was applied in this paper, in order to produce surface roughness data, which adequately fit to measurements on milled specimens. The algorithm implements sub programs, able to determine the produced chips in transient or stable cutting conditions. This kind of information is essential to estimate the cutting force components acting on the cutting tools or on the machine tools. Besides these capabilities, the MSN code contains extended databases of experimentally derived technological parameters, which shall be presented in further research works. The software can be integrated to CAD-CAM systems, extending forward the industrial merit of the program. Considerable attention was paid on the visual representation, in real time, of the cutting process, with respect to educational purposes.
Acknowledgments
This research was financially supported by the Greek General Secretariat for Research and Technology and was carried out in the frame of the “PENED 1999” No 99ED367 research grand. The Authors would like to thank Dipl.Eng. E. Tsagararakis for his software consulting, throughout the developing stage.

References