Simulation of ball end tools milling

by

N. Vidakis¹ A. Antoniadis², C. Savakis³ and P. Gotsis⁴

Abstract
Milling by ball end tools is extensively used for finishing of complex surfaces. The topomorphy of the resulting surface is a research assignment of great interest for many years, whereas various models have been proposed in this area. These models are based on the kinematics of the milling process, following the penetration of the cutting tool into the workpiece, and they calculate the dimensions of the produced chips, the resulting cutting forces and the final topomorphy of the obtained milled surface. This paper exhibits a new simulating model, based on the so-called MSN code (Milling Simulation by Needles). This software is able to find out the produced surface and the resulting surface roughness, in milling with various cutting tools and applying various cutting strategies. The model simulates the kinematics of the tool, determines the influence of the selected cutting geometry to the anticipated roughness, considering the possible tool contact angle with respect to the feed direction. In addition, the simulation of the workpiece differs from other simulation techniques, since the part to be manufactured is decomposed in a finite number of segments, like needles, performing in this way sensible and accurate calculations. A number of simulations have been performed and the resulting surface roughness is calculated against a series of cutting conditions. The simulation model has been also experimentally verified. A number of roughness measurements have been carried out on workpieces machined with the aid of a 5-axes Machining Center. The proposed model is suitable to obtain the optimal cutting conditions for finishing of complex surfaces, either as a stand-alone tool or integrated in any CAD/CAM system.

Keywords: Ball End Tools, Milling, Surface Topomorphy.

1. 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, have to 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 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, is to determine the penetrations of the cutting tool in 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 geometry 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.

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This paper releases an analytical model, which describes the geometry of the milling process with various tools, applied 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 the analysis of the workpiece in a number of finite linear segments, the so-called needles. The model takes into account the orientation of the cutting tool, with respect to the workpiece, offering the possibility to alter the tool inclination angles. On the other hand it can support the 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 the optimal cutting conditions in multi-axis milling, whereas it has been experimentally evaluated through cutting experiments.

2. 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>Simulation</th>
<th>Calculations - Output - Results</th>
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<tr>
<td>Type of Tool - Tool material</td>
<td>Cutting tool model</td>
<td>Mathematical - geometrical description</td>
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<tr>
<td>z : number of flutes</td>
<td>Needles</td>
<td>Undeformed chip cross sections over the development of the cutting edge</td>
</tr>
<tr>
<td>d : diameter [mm]</td>
<td>Workpiece</td>
<td>Analytical assessment of the milled surface topomorphy</td>
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<tr>
<td>a : helix angle [°]</td>
<td>Chip sections</td>
<td>Topomorphy and Roughness</td>
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<tr>
<td>Workpiece material</td>
<td></td>
<td></td>
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<tr>
<td>n, n : parts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Workpiece dimensions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a_i : depth of cut [mm]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>v : cutting speed [m/min]</td>
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Figure 1: The structure of the MSN milling simulating software.

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 initiatory tasks of the simulation algorithm are also illustrated in figure 2. The tool workpiece arrangement is computationally analyzed, in order 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 in \((nt)\) elementary cutting edges, holding a trapezoid shape. This step is presented in the upper right part of figure 2.

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 middle part of figure 2. 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 2. 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

\[
\begin{align*}
s_1 &= (1.0/4.0)*(1.0-r)*(1.0-s) \\
s_2 &= (1.0/4.0)*(1.0+r)*(1.0-s) \\
s_3 &= (1.0/4.0)*(1.0-r)*(1.0+s) \\
s_4 &= (1.0/4.0)*(1.0+r)*(1.0+s)
\end{align*}
\]

**Shape functions**  
Approximate to Triangles : \(ABM = ACM - CDM - DBM\)

**Figure 2:** Simulating principles of the MSN code, for the kinematics and the simulation of the cutting tool.
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.

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<th>Environment of the milling simulation program</th>
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**Figure 3:** Stills from the environment of the MSN software and of the experimental process.

The MSN software was developed in object oriented C++ language. The environment is fully parametric and customizable, whereas it is built in an open and modular structure. **Figure 3** 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 middle left part of figure 3 exhibits a still of the visual simulation of the cutting process, using a ball end tool, with one cutting
edge. Moreover, the bottom left 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 left part of figure 3. The experimental results, besides their aim to validate the MSN software during its development and optimization process, were necessary to correlate parameters, which are not able to be considered during a geometrical simulation. Special roughness measurements (see the bottom right photograph of figure 3), are used to evaluate the experimentally derived surface data.

3. **Analytical and experimental surface results**

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 the upper part of figure 4.

![Chip cross sections](image)

**Figure 4.** Determination of the chip geometry and presentation options.

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 program, since it has implemented cutting force components coefficients for a wide variety of tool-workpiece systems.

In a step forward, the MSN software was enabled to simulate milling operations, applying identical technological and cutting conditions. The middle part of figure 4 shows a typical correlation between the computational and the experimental results. In the specific cutting process, a typical milling case with ball end tool with one, coated cemented carbide edge at low cutting speed is presented. A very characteristic comparison between the analytical and the experimental profiles is presented, where the corresponding analytical and experimental results are put side by side. The correlation between these illustrations is evident. Finally, the bottom left part of this figure illustrates the computationally produced surface map besides a micrograph of the experimentally produced surface (right bottom part of figure 4). In every presentation the experimental and the analytical are in a good agreement, remembering parameters that could not taken into account by the mathematical simulation.

In a step forward, a parametric analysis describing the effect of various cutting parameters on the surface roughness was performed. Figure 5, 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.

**Figure 5:** The influence of the applied cutting feed on the computational and the measured roughness for to different milling kinematics.

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 6 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 6: The possible variations of the milling strategies that MSN software can simulate.

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 optimized.
4. 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.

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5. References


