Prediction of machined surface geometry based on analytical modelling of ball-end milling

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Abstract

This article presents a surface reconstruction model based on a methodology developed for the prediction of cutting forces in free-form milling. From global and local geometry of the tool, initial surface and tool path, this approach allows us to predict cutting forces and now surface form and roughness directly from CAM data. Good results were observed even for complex ball-end milling operations and the idea is to make benefit from the fine geometrical description developed for tool-workpiece engagement calculation to deduce the resultant cut surface. The principle is firstly to store the calculation points coming from the discretization of the cutting tool and identified as engaged in the workpiece material. The second step is to consider a regular grid in plane (X,Y) and to keep the lower points in each created column in order to obtain a Z-Map surface. The procedure of point’s determination, recording and filtering is presented. Moreover, some results are discussed and compared to metrological data.

The conducted milling tests concern a wavelike form with or without transverse inclination produced with a tungsten carbide ball-end mill. The experimental device was mainly composed of classical 3-axes milling machine, a 4 components dynamometer and a dedicated clamping plate. The dynamometer is useful to validate the cutting forces calculation, but in this work, the main interest is to check the stability of the test by observation of forces and frequency responses. The measurements of surface form and roughness were made on a 3D profilometer. This system acquires patches of local micro-topography and allows reconstructing and analyzing several successive tool tracks.

Keywords: Milling ; Surface roughness ; Predictive modelling ; Z-Map

1. Introduction

Ball-end milling is the typical process for the machining of complex surfaces. The machining of such parts presents several difficulties such as tool selecting, the respect of its optimal working zone, part geometry tracking and the good surface finish which is usually targeted. In order to improve the performance of this process the cutting forces have to be calculated accurately and several works were developed in this way.

For example, Yang and Park [1] or Lee and Altintas [2] estimated the cutting forces in ball-end milling for a set of cutting conditions for a machined part, a tool material and geometry with a mechanistic approach of cutting. Fontaine et al. [3] described a complete geometrical model for 3-axes milling and used a thermomechanical oblique cutting model [4] taking into account the part material behaviour and the friction conditions at tool-chip interface.

In recent works [5], a new approach for the modelling of milling was described, where the cutting forces are calculated for milling operations directly from the tool path provided by a Computer Assisted Manufacturing program. The main idea consists in using tool position points coming from CAM data in order to calculate the local inclination angle of the generated surface and then the tool engagement in the machined material. A good approximation for global and local cutting forces can be
obtained when an analytical model able to predict the cutting forces for 3 axes milling is used.

The obtained surface quality is also a key point in optimization of the ball-end milling process. In particular, the resultant surface geometry can be deduced from an accurate modelling of tool path and tool-workpiece engagement. Several authors proposed a Z-Map like representation of machined surface to calculate tool path errors [6], or to estimate the tool engagement in the machined material [7]. A very few works concern the prediction of the resultant surface form or roughness from the geometrical models previously developed for cutting forces calculation [8,9,10,11]. Nevertheless, these surface predictions are limited to form errors in a rigid tool case like in some Computer-Assisted Manufacturing programs. The more advanced methodology presented below allows reproducing also the resultant surface roughness and can be adapted for a flexible tool case.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$R_0$</td>
<td>nominal radius of the tool</td>
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<tr>
<td>$i_0$</td>
<td>global helix angle</td>
</tr>
<tr>
<td>$N_t$</td>
<td>number of teeth of the tool</td>
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<tr>
<td>$\Delta \rho$</td>
<td>transverse sweeping step</td>
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<tr>
<td>$dz$</td>
<td>discretization step of cutter geometry</td>
</tr>
<tr>
<td>$d\theta$</td>
<td>calculation step of tool rotation</td>
</tr>
<tr>
<td>$R_a$</td>
<td>roughness criterion (arithmetic average of the absolute values)</td>
</tr>
<tr>
<td>$R_q$</td>
<td>roughness criterion (quadratic mean)</td>
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2. Reconstruction of the machined surface

2.1. Geometrical description of ball-end milling operations

The global geometry of a ball-end mill can be easily described from its radius $R_0$, helix angle $i_0$ and cutting height, see Fig. 1. The obtained cutting edges along this tool envelope can be divided into a series of elementary cutting edges in oblique cutting conditions [1,2,3,5,7,8]. The local geometry is then described from cutting width, cutting angle, clearance angle and edge inclination angle. The cutting forces can be calculated for each elementary cutting edge, from cutting coefficients [1,2,5,7,8] or even from thermo-mechanical behavior of the cut material [3,4,5] and the global forces are then obtained by summation. At least one point by elementary cutting edge is created to verify the tool engagement in the workpiece material.

The position of these points is calculated from tool rotation and path and often compared to the previous surface (initial or pre-cut one) in order to determine if the cutting forces calculation procedure has to be locally used [3]. This data can be used to analyze the theoretical geometry of the produced surface and even for industrial and complex tool trajectories if CAM data is directly used [5].

2.2. Reconstruction procedure

Then, storing these points’ coordinates at each tool reference position constitutes the first essential phase for the determination of resultant surface. Afterwards, the calculation of the machined Z-map surface is done according the two following steps:

- The first step consists in eliminating the points from the cutting edge which are declared as not engaged in workpiece material (not in cutting position) [3,5], see Fig. 2. The reference positions of the tool are defined by considering step by step that it follows the targeted trajectory on a distance corresponding to the feed per tooth and that it rotates on its axis of an angle corresponding to $2.\pi / N_t$ with $N_t$ the number of teeth of the tool.
The second step consists in suppressing the overlapping due to two adjacent tool trajectories in machining direction, see Fig. 3. It can be done by decomposing the reference horizontal plane (X,Y) into regular elementary cells forming a regular grid, and by keeping only the lowest points (criteria: altitude on Z axis) obtained from the tool engagement procedure in each column.

Fig. 3. 3D representation of points’ overlapping due two adjacent trajectories

The Figure 4 illustrates the final result of the several steps of calculation thus giving a Z-map surface which allows considering a predictive three-dimensional metrology. The resolution of the obtained map depends on calculation increments such as discretization step $dz$ or rotation step $d\theta$, and on the chosen size of grid cells.

Fig. 4. Presentation of the obtained Z-map surface for a wavelike form

2.3. Particularities of predicted Z-map surfaces

The Figure 5 represents a resulting theoretical Z-map surface deduced from the model for a wavelike form [3] obtained in 3-axes milling with a 2 teeth ball-end mill. The black spots correspond to the points selected from the tool engagement procedure.

Fig. 5. Presentation of Z-map surface on 3D and top views for a wavelike form test

In the case described here, it can be observed that during the zigzag sweeping mode, the tool follows the profile with alternation of upward and downward ramping sequences. The down-ramping configuration can make appear zones empty of points and the up-ramping one usually presents a very regular points’ distribution. The empty zones are due to the use of the tool tip to generate the surface and to the absence of edge points because of the vertical discretization of the tool. The importance of the vacuums depends on the discretization step noted $dz$. Indeed, if the value of $dz$ is too high, the first point of engagement resulting from this decomposition is shifted compared to the tool end. By decreasing the increment $dz$, this vacuum effect can be controlled and limited. An increment $dz$ lower than the nominal radius of the tool $R_0$ divided by 50 generally gives good results. It can be selected to reveal knowingly these vacuums because they highlight the zones where the hemispherical tool is in unfavorable cutting position and where more roughing than shearing will be at the origin of the material deformation. This roughing phenomenon is the result of machining with a too thin chip thickness and a too limited cutting speed, and it has a direct negative impact on the surface quality. Then, this modelling "defect" can be used like criterion of detection of cutting problems. The increment $dz$ can then be used as a regulating parameter to create a size of vacuum corresponding to the size of the zone to avoid on the tool.

3. Experimental validation

3.1. Milling tests

To validate the calculated Z-map surfaces, several wavelike form tests [3], Fig. 4, were performed on a 3-axes milling machine, see Fig. 6. The tool was a 12 mm diameter tungsten carbide ball-end mill with two teeth. Two configurations are presented here: roughing with a
transverse sweeping step of $\Delta p = 2$ mm and finishing with $\Delta p = 0.5$ mm. The cutting forces were also measured in order to check the cutting stability. A specific device composed in a dynamometer, a charge amplifier and acquisition PC and software, was used in this way.

3.2. 2D/3D Surface metrology

The measurement of the surface quality was made on a non-contact 2D/3D surface metrology system Alicona InfiniteFocus, see Fig. 7. This system acquires images of surface micro-topography reconstructed from a series of partially focused images. It combines the advantages of a microscope and of a profilometer and the resolution on z-axis is inferior to 20 nm. Dimensional and normalized analyses can be performed in 2D and 3D. Moreover, topography maps and microscopy images can be superposed and observed simultaneously.

The entire workpiece presents an initial surface of 50×50 mm$^2$ and a whole surface acquisition with a good resolution is very time-consuming (dozens of hours). That is the reason why measurements on patches of several mm$^2$ were mainly conducted at several positions along the tool path.

3.2.1. Measurements for roughing test ($\Delta p = 2$ mm)

A surface of 4×6 mm$^2$ of the workpiece was rebuilt numerically patch by patch using the 3D profilometer with a resolution of 500 nm, see Fig. 8.

The data processing software allows measuring roughness according to a line or a band of our choice (longitudinal or transverse roughness in our case), see Fig. 9. The result is presented in the form of a graph and can be exported in tables.

3.2.2. Measurements for finishing test ($\Delta p = 0.5$ mm)

A surface of 7×7 mm$^2$ of the workpiece was rebuilt numerically patch by patch using the 3D profilometer

Fig. 6. Vertical 3-axes milling machine used in experiments.

Fig. 7. System used for the analysis of surfaces quality

Fig. 8. Patch of acquisition (4×6 mm$^2$)

Fig. 9. (a) Longitudinal and (b) transverse roughness according to the machining direction
with a resolution of 50 nm, see Fig. 10. Roughness measurements follow here the same method than for the previous roughing test. The altitude of each point can be analysed through the topography reconstructed by the software.

![Fig. 10. (a) Acquisition patch and (b) surface topography (7×7 mm²)](image)

In order to study the evolution of roughness along a tool path, a patch with a dimension of 1.6×50 mm² was reconstructed, see Fig. 11. Three tool tracks are observable and hence all the configurations of up and down ramping and of up and down cutting can be analysed.

![Fig. 11. (a) Acquisition patch and (b) surface topography for 3 tool tracks (1.6×50 mm²)](image)

### 3.2.3. Comparison between measured and predicted roughness

The comparison presented here is resulting from the tests firstly conducted to validate the cutting force model. The selected tests where checked in terms of stability and tool wear in order to compare relevant information to the results of simulation. These results are limited to the transverse roughness on a patch of finishing sweeping (7x7mm) of the wave surface, see Fig. 10.

Transverse roughness for two corresponding surfaces (measured and simulated) in finishing ($\Delta p = 0.5$ mm):

- Arithmetic average of the absolute values:
  \[ R_a \text{ measured surface} = 2.63 \mu m, \quad R_a \text{ simulated surface} = 2.71 \mu m \]

- Quadratic mean of the variations:
  \[ R_q \text{ measured surface} = 3.14 \mu m, \quad R_q \text{ simulated surface} = 3.33 \mu m \]

It can be noted that the discrepancy is very low (0.08 $\mu m$ on $R_a$ and 0.19 $\mu m$ for $R_q$) especially when considering that the model in this version is limited to a rigid tool case. These first results are very encouraging and indicate that the model seems able to calculate and simulate accurately the resulting surface.

The pertinence and precision of the obtained geometry depend on the calculation increments $dz$ and $d\theta$ used in the decomposition of the tool envelope and its rotation respectively. The step of the used grid is also very influential and a value of this step inferior to the feed per tooth must be used in order to reproduce the roughness in feed direction. The transverse direction (sweeping direction) roughness is easier to obtain because the path interval $\Delta p$ is usually higher than the feed per tooth.

The validation has to be performed further especially for different finishing configuration tests with varying cutting conditions and sweeping strategies.

### 4. Conclusion

The model described here, previously developed for the prediction of cutting forces in free-form milling, enables to study the resultant surface quality by recording the cutting edges points engaged in the workpiece and by identifying and keeping the lower points in each cell of a regular grid (Z-map method). Each point $P$ considered in the cutting forces calculation is then recorded and this data is treated to obtain a 3D picture of the theoretical machined surface. The first results obtained correspond to a rigid tool case and the global geometrical characteristics of the machined surface are reproduced: form, transverse picks and valleys, theoretical roughness. In order to compare them more accurately with real machined surfaces, it can be interesting to take into account the flexibility of tool and tool-holder. An analysis of the variations has to be made to check the precision of the simulation results and to improve our trust in the predictions to come on surface quality.

The context of these works is to propose efficient tools for the optimization of complex milling operations, see Fig. 12. The prediction of the cutting forces thus
permits the optimization of cutting conditions and trajectories of tools. Applications of this type of model are numerous and concern the global optimization of the manufacturing process. For example, tool deflection can be estimated from the calculated cutting forces to compensate the tool trajectory with the purpose to respect the manufacturing tolerances. The modelling of vibrations is also possible from this data and the dynamic behaviour of the active part (tool, tool-holder and spindle) can be analysed. Stability lobes associated to the process can be then determined and they allow selecting the optimal cutting conditions in terms of tool life and surface quality. The study of residual stresses on the part and of tool wear can be enriched too by this information. The temperature fields at the tool-chip interface can be also accessible thanks to the use of appropriate thermomechanical models to describe the material behaviour and the friction conditions. Finally, it has been shown that the predetermination of the quality of manufactured surfaces can be assumed by the used of the proposed model. All these themes illustrate well the interest to develop realistic and physical simulation tools to optimise the machining processes.

References