3D FE-based Modelling and Simulation of the Micro Milling Process
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Abstract. Modelling and simulation of the micro milling process has the potential to improve tool design and optimize cutting conditions. This paper presents a novel and effective 3D finite element (FE) based method for simulating the micro milling process under large deformations. A tooling model incorporating a helix angle is developed for cutting forces, tooling temperature and chip formation prediction. The proposed approach is experimentally validated and the simulated micro milling performance such as micro chip formation and cutting forces are in reasonable agreement with the measured results in cutting trials.

1 Introduction

In micro manufacturing, micro milling represents an emerging technology capable of fabricating 3D freeform miniature and micro components or features with high accuracy in a direct and cost-effective manner. Modelling and simulation of the cutting process potentially allows designers and engineers to reduce the need for costly shop-floor trials, improves cutting tool design, optimizes process conditions and shortens the lead time in bringing a new product into the market. The finite element method (FEM), featuring reasonably accurate predictions on a user friendly graphical interface, has been widely employed for cutting processes modelling, simulation and optimization [1-3]. However, applying FEM for 3D micro milling analysis is seldom reported, although 3D comprehensive analysis is essential and has many advantages in addressing the complexity in micro milling quantitatively.

Dhanorker et al. [4] developed a 2D rigid-plastic model to predict cutting forces, temperature distribution and chip formation in meso/micro scale milling processes and Wang et al. [5] studied the micro chip formation mechanism by adopting a similar simulation approach. Afazov et al. [6] performed a number of 2D orthogonal cutting simulations to investigate micro milling forces indirectly. In the study, cutting forces were calculated based on a combination of simulation results and mathematical models. The models and simulation above are only under plane strain deformation and no 3D models incorporating a helix angle are developed. Micro milling is an intermittent cutting process, and setting the flutes at an angle allows the tooth to engage work material gradually and smoothly so as to reduce vibration. Also, the helix angle plays as a significant role in evacuating chips. Furthermore, there is a considerable difference between cutting edge contact length with and without a helix angle. For the 2D model, chips only deform in planar directions, resulting in inaccurate prediction of chip flow directions and shapes. Therefore, the plane strain model is relatively inaccurate for representing the practical cutting process, and micro milling simulations should ideally take helix angle effects into account.
This paper presents a novel rigid-plastic finite element approach for modelling and simulation of the micro milling process. A 3D tooling model considering helix angle is developed for cutting forces, tooling temperature distributions and chip formation prediction. Comparisons of predicted chip formation and cutting forces with experimental results in dry slot milling are conducted for evaluation and validation of the proposed model.

2 Simulation developments

Micro milling simulation is developed using DEFORM™-3D, a robust computational tool capable of analyzing 3D complex machining processes. It employs the updated Lagrangian formulation for implicit analysis and features automatic and optimized remeshing ability under large deformations. Deformation and heat transfer are calculated in an integrated manner. A maximum plastic strain failure criterion is adopted for chip separation and element separation occurs when a material critical plastic strain is reached. In the study, the micro cutter was assumed to be rigid, and the work piece possessed a homogeneous microstructure and performed plastic deformations.

2.1 Tool modelling, meshing and boundary conditions

A Ø0.3 mm diameter two-fluted end mill with a 30° helix angle was used in the modelling. Tool geometries including a 7° rake angle, 15° relief angle and 2.5µm cutting edge radius were measured by a scanning electron microscope and the tungsten carbide tool is shown in Fig.1. For micro end milling, the primary cutting edge is the side edge whereas the minor cutting edge is the bottom edge, and chip removal is mainly performed by the side cutting edge. Since feed per tooth is relatively low compared to axial depth of cut, the bottom cutting edge was ignored for modelling. The primary cutting edge model, incorporating tool diameter, rake angle, relief angle, cutting edge radius and helix angle, was developed through helical sweep protrusion by the commercial software Pro/Engineer. As for tools with helix angle, pitch height can be calculated by:

\[ P = \frac{2\pi R}{\tan(\beta)} \]  

where \( \beta \) and \( R \) are helix angle and tool radius respectively. The pitch height for a Ø0.3mm diameter end mill with a 30° helix angle is 1.6324 mm.

For tool meshing, tetrahedral elements and a mesh density window were used. Size ratio was set at 0.1, and meshing of the primary cutting edge model is shown in Fig.2. The total numbers of nodes and elements in the meshing were 3,165 and 13,181. For boundary conditions, heat exchanges between tool surfaces and environment were considered.
2.2 Work piece modelling, meshing and boundary conditions

Simulation of full immersion milling was carried out. The modelling, meshing of work piece, cross-sectional dimensions and boundary conditions are shown in Fig. 3(a-c). A 180° rotational angle work piece was modelled by Pro/Engineer. For meshing, tetrahedral elements and a mesh density window were adopted. The meshing window follows the movement of the tool during simulation to ensure sufficient elements around the tool-work interface area. The total numbers of nodes and elements are 4,646 and 19,299 respectively. As shown in Fig.3(c), velocities of deformation boundary surfaces are fixed in three orthogonal directions and there exists thermal exchange between other free surfaces and the environment.

![Fig.3 Work piece modelling, meshing, cross-sectional dimensions and boundary conditions](image)

2.3 Work material flow stress

Iqbal, S.A. et al. [7] compared different flow stress models with experimental results for AISI 1045 steel and pointed out that the Johnson-Cook constitutive model produces the lowest percentage force errors at low, medium and high temperatures, and is recommended for cutting simulations over a wide range of cutting speeds. Therefore, a Johnson-Cook work material model was selected for coupled thermal deformation analysis. The Von Mises flow stress can be represented as follows:

\[
\sigma = [A + B(\varepsilon^P)] \left[ 1 + C \ln \left( \frac{\varepsilon^P}{\varepsilon_0} \right) \right] \left[ 1 - \left( \frac{T - T_{\text{Room}}}{T_{\text{Melt}} - T_{\text{Room}}} \right)^{\frac{n}{m}} \right]
\]

where \(\varepsilon^P\) is the equivalent plastic strain, \(\dot{\varepsilon}^P\) is the plastic strain rate, \(\varepsilon_0\) is the reference strain rate (normally \(\varepsilon_0 = 1.0 \times 10^{-5}\)), \(T_{\text{Melt}}\) and \(T_{\text{Room}}\) are melting temperature and room temperature, and A, B, C, m, n are material constants. The Johnson-Cook constants for AISI 1045 steel, listed in Table 1, were determined by compression tests [8].

<table>
<thead>
<tr>
<th>A (MPa)</th>
<th>B (MPa)</th>
<th>C</th>
<th>n</th>
<th>m</th>
<th>(T_{\text{Melt}}) (K)</th>
<th>(T_{\text{Room}}) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>553.1</td>
<td>600.8</td>
<td>0.0134</td>
<td>0.234</td>
<td>1.0</td>
<td>1733</td>
<td>293</td>
</tr>
</tbody>
</table>

2.4 Chip-tool interface friction

The contact schemes and the friction coefficients between the tool and the chip are affected by various factors, such as material properties, cutting conditions, tooling geometries, etc. Pure sliding is an appropriate friction scheme for conventional machining while in high speed cutting, sliding integration of a sticking model should be considered in terms of minor error of cutting forces [7]. For micro milling, a higher spindle speed is chosen to achieve higher cutting speed; however, compared to conventional machining, cutting speed is relatively low due to the smaller tool diameter. Therefore, a pure sliding pattern is assumed reasonable and applicable. Based on Coulomb’s law, the mathematical expression for frictional stress \(\tau_f\) on tool rake surface is given by:
where, $\sigma_n$ is the normal stress and $\mu$ is the coefficient of friction.

The interface friction coefficient between tungsten carbide and AISI 1045 was estimated to be 0.4, which is based on a pin-on-disk test [9].

### 2.5 Process conditions and materials properties

Table 2 illustrates the process conditions, and tool and work material properties used for simulation. The properties of tool and work piece are derived from the simulation software database and www.matweb.com.

**Table 2** Summary of process conditions, and tool and work material properties for simulation inputs

<table>
<thead>
<tr>
<th>Process conditions:</th>
</tr>
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<tbody>
<tr>
<td>Spindle speed: 30000 rpm</td>
</tr>
<tr>
<td>Feed per tooth: 1 $\mu$m</td>
</tr>
<tr>
<td>Axial depth of cut: 20 $\mu$m</td>
</tr>
<tr>
<td>Initial temperature for tool and work piece: 20 °C</td>
</tr>
<tr>
<td>Convection coefficient: 0.02 N/sec/mm/°C</td>
</tr>
<tr>
<td>Heat transfer coefficient: 45 N/sec/mm/°C</td>
</tr>
<tr>
<td>Fraction of deformation energy transformed into heat: 0.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tungsten carbide properties:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson’s ratio: 0.24</td>
</tr>
<tr>
<td>Young’s modulus (GPa): 690</td>
</tr>
<tr>
<td>Thermal conductivity (W/m/K): 84.02</td>
</tr>
<tr>
<td>Specific heat (J/kg/K): 203</td>
</tr>
<tr>
<td>Thermal expansion coefficient ($\mu$m/m/°C): 5.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AISI 1045 steel properties:</th>
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</thead>
<tbody>
<tr>
<td>Poisson’s ratio: 0.29</td>
</tr>
<tr>
<td>Young’s modulus (GPa): 205</td>
</tr>
<tr>
<td>Thermal conductivity (W/m/K): 49.8</td>
</tr>
<tr>
<td>Specific heat (J/kg/K): 486</td>
</tr>
<tr>
<td>Thermal expansion coefficient ($\mu$m/m/°C):</td>
</tr>
<tr>
<td>0 °C 11.7 11.9 12.5 13 13.6 14.1 14.5 14.9 14.9</td>
</tr>
<tr>
<td>20 °C 1500 °C</td>
</tr>
</tbody>
</table>

### 3 Simulation results

The simulation was carried out under large deformations without considering process dynamic influences. Predicted cutting forces in three orthogonal directions in one cutting passage are illustrated in the following validation section (see Fig.9) and maximum feed force, normal force and axial force are 187 mN, 212 mN and 49.2 mN. The estimated tooling temperature distributions at different rotation angles are shown in Fig.4, and the maximum tooling temperature at 45°, 90° and 135° are 49 °C, 78 °C and 110 °C, respectively.

![Fig.4 Predicted tooling temperature distributions at different rotation angles](image)

Chip formation prediction at 45°, 90° and 135° rotational angle cutting are shown in Fig.5. It is obviously seen that chips flow along the tool helical direction, which reasonably matches practical micro milling operation. At a 45° rotational angle, radial depth of cut is considerably smaller
compared to the cutting edge radius and chips appear straight, largely due to the size effect-related negative rake angle effect in the micro-scale cutting. Along with increasing radial depth of cut to feed per tooth as shown in Fig.5 (b), a complete spiral chip is produced as a result of helix angle influence. When the cutting edge reaches the position of 135° rotational angle, fractured chip is observed owing to maximum plastic strain failure criterion applied in the simulation.

![Fig.5 Chip formation at different rotation angles](image)

4 Validation through cutting trials

Comparison of predicted chip formation and cutting forces with experimental results were adopted to verify the simulation results. Dry slot milling on an AISI 1045 sample was carried out on an ultra precision micro milling machine, UltraMill (see Fig.6). Cutting forces were recorded by a Kistler dynamometer MiniDyn 9256C2 with a charge amplifier of 5070A. The sampling rate was set at 32000 Hz, which enabled sufficient sampling points in one recorded cutting passage. A digital camera was employed for micro tool alignment. The setup of the cutting trials is shown in Fig.7.

![Fig.6 Micro milling machine UltraMill](image)  ![Fig.7 Setup of the cutting trials](image)  ![Fig.8 Example of micro chip](image)

Machined micro chips were collected and observed under the digital microscope Keyence VHX-1000. The predicted spiral shaped chip, as previously shown in Fig.5(b), was in good agreement with the micro chip example (see Fig.8). In addition, averaged cutting forces in five consecutive cutting paths together with the predicted counterparts are compared in Fig.9, and they are well matched, which demonstrates the acceptable accuracy of the simulation results. Based on the above comparison and analysis, the simulation is believed to be correct and convincing, and the proposed model could provide reasonable accuracy for scientific understanding and characterization of the micro milling process. The results above are also supportive of the cutting trials previously undertaken [10].

![Fig.9 Comparison of cutting forces](image)
5 Conclusions

In this paper, a novel 3D FE-based method was proposed for modelling and simulation of the micro milling process. Simulations considering tooling helix angle under large deformations were carried out using a commercially available tool DEFORM™-3D. Cutting forces, tooling temperatures and chip formation in the simulation were presented. Predicted micro chip formation and cutting forces show reasonable agreement with the experimental results, which demonstrates that the proposed modelling and simulation approach are capable of characterizing the micro milling process with acceptable accuracy.

Acknowledgments

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References