PPREDICTION OF CUTTING FORCES IN MICRO-MILLING PROCESS USING FINITE ELEMENT METHOD

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ABSTRACT

This paper presents the prediction of micro-milling forces using the finite element method (FE). An FE model of orthogonal micro-cutting with round cutting edge is developed. The cutting force coefficients are identified from a series of FE simulations at a range of cutting edge radii and chip loads. The identified cutting force coefficients are used to simulate micro-milling forces. The simulation results are experimentally validated in cutting tests with a 200 µm diameter helical end micro-mill.

Keywords: Micro-milling, Finite element, Cutting force.

INTRODUCTION

Micro-milling is used in biomedical, electronics, sensors, die and mold industry to produce miniature components.

The diameter of the micro mills ranges from 25 µm to 1.0 mm, with flute heights of 2 mm to 10 mm and cutting edge roundness of 1 µm - 20 µm depending on the application. The size of the chip loads is comparable with the tool edge radius in micro-milling; hence chip formation occurs around the round cutting edge zone. Tool geometry, cutting speed, chip load and depth of cut must be properly selected to avoid premature wear and breakage of the micro-mills, as well as producing smooth surface finish with desired accuracy on the miniature parts.

The mechanics and dynamics of micro-cutting must be modeled in order to predict the process behavior ahead of costly physical trials. The prediction of cutting forces, temperature distributions and vibrations by relying on the work material properties, tool geometry and cutting conditions has been increasingly studied in recent years.

The chip is partially sheared and plastically ploughed around the round cutting edge. Park and Malekian [1] proposed a mechanistic force model which considered both the shearing and ploughing dominant cutting regimes, and considered the effect of tool edge radius indirectly. Dhanorker and Ozel [2] developed the FE model of meso/micro scale milling and predicted the chip formation, temperature and cutting forces. Childs [3] investigated the size effects and modelled the cutting force as a function of shear angle, tool edge radius and uncut chip thickness. Afazov et al. [4] modelled the milling forces from finite element simulation of orthogonal cutting by including the effect of uncut chip thickness, tool edge radius and cutting velocity. Simoneau et al. [5] included the microstructure effects in the micro-cutting of steel.

This paper presents an FE model in simulating micro-milling forces from material’s constitutive model and friction parameters between the tool and chip materials. The strain hardening, strain-rate and temperature effects are included in the material property. The tool-chip friction parameters are based on the experimental identification through slip-line field model proposed by the authors in [6]. The predicted cutting forces are used to express cutting force coefficients as nonlinear functions of tool edge radius and uncut chip thickness, mimicking mechanistic models. The milling forces are then predicted by adjusting the cutting force coefficients as the chip varies. The predicted cutting forces are experimentally validated. Tool geometry, run-out and the effects of dynamometer dynamics are considered.

CUTTING FORCE COEFFICIENT ESTIMATION FROM FE MODELING

The FE model of orthogonal micro-cutting process is developed using ABAQUS/Explicit 6.8-3 [7]. The effect of the tool edge radius is included in the FE model as shown in Fig. 1. Plane strain cutting condition is considered in the FE analysis. The workpiece moves towards the fixed tool with velocity v. The tool is modeled as an isothermal rigid body. The workpiece is meshed by the four-node thermally coupled
quadrilateral elements. Arbitrary Lagrangian Eulerian (ALE) adaptive meshing is used to avoid the excessive distortion of the element. Due to the high cutting speed, adiabatic thermal-stress analysis is applied by neglecting the convection and radiation.

Brass 260 is used as the workpiece material in the model. The Johnson-Cook constitutive model [8] is applied to include the strain hardening, strain-rate, and thermal softening effects on the flow stress of the material, which is expressed as:

$$
\sigma = \left( A + B \dot{\varepsilon}^n \right) \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - \left( \frac{T - T_m}{T_r - T_m} \right)^m \right]
$$

where $\dot{\varepsilon}$ and $\dot{\varepsilon}_0$ are the equivalent and reference plastic strain rates, $T$, $T_m$ and $T_r$ are the material's cutting zone, melting and room temperature, respectively, $n$ is the strain hardening index, and $m$ is the thermal softening index. Parameters $A$, $B$ and $C$ represent the yield strength, strain and strain-rate sensitivities of the material.

The sticking and sliding contacts between the tool and the workpiece are considered. In the sticking contact region, a constant frictional stress $\tau$ is applied due to the high normal stress on the cutting tool. The sliding contact satisfies the coulomb friction law with a constant coefficient of friction $\mu$.

A series of brass cutting simulations are performed at different uncut chip thicknesses ($h \in [0.1, 0.20] \mu m$) and tool edge radii ($r \in [1, 8] \mu m$). Fig. 2 shows the evolution of tangential and feed forces with respect to time. The forces reach the steady state and the final values are recorded.

The predicted cutting forces with respect to the uncut chip thicknesses and tool edge radii are shown in Fig. 3. The cutting forces are modeled as:

$$
F_i = K_i(h, r) h w; \quad F_f = K_f(h, r) h w
$$

where the cutting force coefficients are curve fitted to the simulated forces as follow:

$$
K_i(h, r) = K_{i_1}(h) + K_{i_2}(h, r) = \alpha_i h^{n_i} + \beta_i h^{n_i} r^{n_i}
$$

$$
K_f(h, r) = K_{f_1}(h) + K_{f_2}(h, r) = \alpha_f h^{n_f} + \beta_f h^{n_f} r^{n_f}
$$

The empirical constants ($a$, $b$, $d$, $p$ and $q$) relate the sensitivity of the forces to the edge radius and chip thickness. The identified constants in Eq. (4) are listed in Table 3.

Table 1: Johnson-Cook Parameters of Brass 260 [6]

<table>
<thead>
<tr>
<th>$A$ [MPa]</th>
<th>$B$ [MPa]</th>
<th>$C$ [-]</th>
<th>$n$ [-]</th>
<th>$m$ [-]</th>
<th>$T_m$ [°C]</th>
<th>$T_r$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>404</td>
<td>0.009</td>
<td>0.42</td>
<td>1.68</td>
<td>916</td>
<td>25</td>
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</tbody>
</table>

Table 2: Physical Properties of Brass 260

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m$^3$]</td>
<td>8500</td>
</tr>
<tr>
<td>Elastic Modulus [MPa]</td>
<td>110000</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>Conductivity [W/m°C]</td>
<td>109</td>
</tr>
<tr>
<td>Specific Heat [J/kg°C]</td>
<td>377</td>
</tr>
<tr>
<td>Inelastic Heat Fraction</td>
<td>0.9</td>
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Table 3: Constants for the cutting force coefficients of material Brass 260 at cutting speed 25 m/min. Units of chip thickness and edge radius are in [mm].

<table>
<thead>
<tr>
<th>$K_i$ [MPa]</th>
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<th>$d$</th>
<th>$\beta$</th>
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<tr>
<td>1744</td>
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<td>181.2</td>
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Fig. 2 Cutting forces with time. Uncut chip thickness = 4μm, Cutting speed = 25 m/min, tool's primary rake angle = 5 deg. The predicted cutting forces with respect to the uncut chip thicknesses and tool edge radii are shown in Fig. 3. The cutting forces are modeled as:

$$
F_i = K_i(h, r) h w; \quad F_f = K_f(h, r) h w
$$

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PREDICTION OF MICRO-MILLING FORCES

The cutting force coefficients identified from the FE model are used to predict micro-milling forces. Tangential ($dF_t$) and radial ($dF_r$) forces acting on a cutting edge with a differential depth of cut $dz$ are expressed as (Fig. 4):

$$dF_t(\phi) = K \ h(\phi) \ dz \quad dF_r(\phi) = K \ h(\phi) \ dz \quad \phi \in (\phi_e, \phi_a)$$  \hspace{1cm} (5)

where $\phi$ is the instantaneous immersion angle of the tool, and $\phi_e$ and $\phi_a$ are the entrance and exit angles of the cutter, respectively. The forces are zero when the edge is out of cut. The instantaneous chip thickness $h(\phi)$ is evaluated by considering the exact kinematics of the milling [9], general tool geometry and the effect of radial run-out of flutes [10]. The elemental forces are resolved into feed and normal directions:

$$dF(\phi) = -dF_c \cos(\phi) - dF_s \sin(\phi)$$
$$dF(\phi) = dF_c \sin(\phi) - dF_s \cos(\phi)$$  \hspace{1cm} (6)

The total milling forces are evaluated by integrating all the elemental forces contributed by N flutes ($i$) along the axial depth of cut ($a$).

$$F(\phi) = \sum_{i=1}^{N} dF_t[i \phi + (i-1) \frac{2\pi}{N}] d\phi \quad F(\phi) = \sum_{i=1}^{N} dF_r[i \phi + (i-1) \frac{2\pi}{N}] d\phi$$  \hspace{1cm} (7)

The helix angle and radial run-out of the flutes are also considered in the model. The details of the general milling model have been presented before by Altintas et al. [9][10], and the algorithms have been integrated into an advanced milling process simulation system [11] and used in predicting micro-milling forces, vibrations, dynamic chip thickness and surface roughness errors.

EXPERIMENTAL VALIDATION

The micro-milling tests have been performed on MIKROTOOL micro-machining center having a spindle speed range of 60,000 rev/min. The experimental setup is shown in Fig. 5. A two-flute carbide micro end mill (MITSUBISHI MS2MS) with 200 µm diameter and 30° helix angle is used in milling Brass 260 with 75 HRB hardness. Tool edge radius of the micro mill was measured to be 3.7 µm with an optical microscope shown as Fig. 4. The static run-out at the end mill tip was measured to be 0.6 µm with an optical microscope. The workpiece was fixed on a Kistler 9256 three component mini-dynamometer to measure the cutting forces. The vertical position of the tool tip with respect to the workpiece was aligned by moving the cutting tool down to the workpiece very slowly while a low voltage is applied on both tool and workpiece. The reference position was recorded when the tool came into contact with the workpiece and a short circuit signal was triggered.

Several cutting tests at different spindle speeds and feed rates have been conducted. The tool was inspected for wear and damage after each cut by a microscope integrated to the machine. The measured frequency response function (FRF) of the dynamometer indicates a bandwidth of 2000 Hz. Unless compensated, the harmonics of the milling forces may cause poor measurements with the dynamometer.

Sample experimental and simulation results are given in Fig. 7. Speeds between 45,000 and 60,000 rev/min have been deliberately avoided to prevent resonating the two modes (3400 Hz and 3000 Hz) of the dynamometer. The dynamometer’s modes are still slightly excited by the harmonics of high tooth passing frequencies (666 Hz and 1333 Hz), and appeared as distorted oscillations on the raw measurement data. The measured forces are Kalman filtered [12] to compensate the distortion of cutting forces caused by the dynamometer dynamics. The simulations are carried out by using the cutting force coefficients predicted from FE simulations. The tool run-out, helical flute, edge geometry is considered, as well as the effect of the exact chip size as the
tool rotates by the simulation system [11]. The simulated cutting forces in Y direction agree well with the experimental results. The discrepancy of the cutting forces in X direction may be due to the cutting force prediction from the FE model. Filize et al. [13] reported the underestimation of the FE simulated feed force compared to the experimental data by 30% when the sticking-sliding tool-chip contact is modeled. Rech et al. [14] included the tool edge radius in the FE model and showed that the simulated feed forces are less than 50% of the experimental values.

CONCLUSIONS

The paper illustrated the prediction of micro-milling forces from the FE model. The cutting force coefficients were identified as a function of chip thickness and tool edge geometry. The cutting coefficients were used in milling model which considered the helix angle, run-out and dynamics of the dynamometer. The simulated milling forces were compared with the experimental results.

ACKNOWLEDGMENTS

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REFERENCES


Fig. 7 Slot micro-milling with 50 μm axial depth of cut. Material: Brass 260. Tool: 200 μm diameter with two 30 degree helical flutes. Edge radius: 3.7μm, run-out: 0.6 μm.