Finite Element Simulations for Micromilling of Oxygen-free Copper

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Abstract. Micromilling mechanism studies are the fundamentals for high-quality micro components fabrications. Based on the finite element method (FEM), the simulation model for micromilling of the oxygen-free copper (OFC) was established in this paper. The influences of the key process parameters (feed engagement \( f_z \), axial depth of cut \( a_p \), radial depth of cut \( a_e \), and spindle speed \( n \)) on the milling forces were investigated. According to the simulation results, to achieve the minimum undeformed chip thickness, the critical feed engagement was identified to be 2.5 \( \mu m/z \). When the axial depth of cut increased, the milling force was increasing linearly, but at the same time the milling force took an oscillator decreases due to the increasing of spindle speed. The overall trend of milling force under different radial depths of cut is upward. Therefore, the feed engagement should be greater than 2.5 \( \mu m/z \) for micro milling of oxygen-free copper. Small radial depth of cut, small axial depth of cut, and appropriate spindle speed should be selected to obtain a high machining quality.

Introduction

As an excellent metal with extremely low oxygen content, high conductivity and high corrosion resistance, oxygen-free copper C10100 is widely used in the manufacturing of audio-visual equipment and communication components. With good ductility and no hydrogen embrittlement, it can also be processed into various precision micro parts. Compared with traditional cutting, high-speed micromilling is more suitable for machining micro-small parts. In order to obtain higher dimensional accuracy and better surface quality, it is necessary to study the milling parameters of OFC in the processing of precision parts. In the actual machining process, the changes of milling force caused by the changes of milling parameters can reflect the quality of the final machined parts more intuitively. Therefore, the adjustment of milling parameters can be guided by measuring the milling force in the milling process.

In order to reveal the difference in mechanism between traditional cutting and micromilling, scholars have conducted a lot of studies. In the study of cutting poly-crystalling OFC with single crystalline diamond (SOD) micro-tools, X. Ding has proposed that the cutting strategy of reducing cross-feed can improve the cutting performance with using micro-tools. Constant cutting forces, burr size and an improved roughness of the machined surface have been obtained by employing this cutting strategy [1]. Niu has presented an innovative cutting force modeling concept by taking account of micro-cutting dynamics. Experimental cutting trial is conducted to validate the modeling approach and the cutting force model [2]. Qu has studied the impact of MQCL method on the machining results and mechanical properties of the component [3]. Yuan has proposed an innovative uncut chip thickness algorithm and developed the model for determining the instantaneous uncut chip thickness in micro end-milling processes [4]. D.DAS has studied the effect of stress parameters on ratcheting deformation stages of polycrystalline OFHC copper [5]. For the micromilling of pure copper, M. Rahman has studied the failure mechanism and factors which affect the micro end mill [6]. Liu has studied the relationship between size effect and burr in micromilling OFC and constructed a geometric model of exit burrs [7]. Liu has established SPH simulation model and carried out systematic research on formation mechanism of chip [8]. For oxygen-free copper materials, Tian has established a constitutive model and carried out simulation analysis based on Abaqus [9]. Cheng has proposed...
three categories of micromilling processes under different radial depth-of-cut and defined the formula of undeformed chip thickness (UCT) $h$ [10].

In previous studies, there are so little studies for the micromilling force of oxygen-free copper. Milling force is an important index in the study of micromilling. By analyzing micromilling force and selecting milling parameters, better machining quality of parts can be obtained under certain rigidity of machine system. In this paper, based on the finite element method (FEM), the influence trends of four key micromilling parameters ($f_z$, $a_p$, $a_e$, $n$) on the milling force in micromilling were studied by using single factor experimental method. The conclusion of simulated experiments has great value for actual micromilling of OFC.

Simulation Setup

Finite Element Modeling

The finite element simulation software Deform-3D used in the simulation experiments has high accuracy for the cutting simulation of metal materials. Before the simulation experiments, the 3D models of micro end tool and workpiece are established by SolidWorks. The diameter of micro end tool is 500 μm, the radius of the cutting edge is 5 μm and the tooth number is 2. The size of workpieces is 350μm×350μm×350μm and it has been pre-cut to improve the simulation efficiency. The models of micro end tool and workpiece are shown in Fig. 1(a). In the meshing process, local mesh refinement is carried out for the workpiece and cutter to improve the simulation accuracy, the simulation model after meshing and mesh refinement is shown in Fig. 1b. The workpiece material is oxygen-free copper C10100, the tool material is cemented carbide.

![Figure 1. The simulation model.](image)

Simulation Parameters

Four key parameters ($f_z$, $a_p$, $a_e$, $n$) in micromilling are selected as variables and five values are set for each variable based on previous studies. The parameters selections for each group simulation experiment are shown in Table 1.

| No. | Simulation Factors | Axial depth of cut $a_p$ [μm] | Radial depth of cut $a_e$ [μm] | Feed engagement $f_z$ [μm/rev] | Spindle speed $n$ [min⁻¹] |
|-----|--------------------|-------------------------------|-------------------------------|-------------------------------|--------------------------|
| 1   |                    | 30                            | 50                            | 0.5, 1.5, 2.5, 3.5, 4.5       | 60000                    |
| 2   |                    | 20, 30, 40, 50, 60            | 50                            | 2.5                           | 60000                    |
| 3   |                    | 30                            | 50                            | 2.5                           | 50000, 55000, 60000, 65000, 70000 |
| 4   |                    | 30, 50, 65, 80, 95, 110       | 2.5                           | 60000                         |
Simulation Results Analyses

Micromilling Force

The milling forces in three directions in each group of simulation experiments can be obtained through finite element analyses. When the feed engagement is 2.5 μm/z, the axial depth of cut is 30 μm, the radial depth of cut is 50 μm and the spindle speed is 55000 min⁻¹, the simulated results of milling forces in three directions are shown in Fig. 2. It can be seen that after a period of cutting, the milling forces in all directions tend to be stable. The data used in the simulation analyses are the milling forces in all directions after the stability micromilling.

When the milling forces are calculated, the milling forces in three directions under the stable milling state are selected and the invalid points have been removed. The average value of multiple groups of micromilling is taken as the milling forces in x, y and z directions respectively. The resultant milling force is obtained by Eq. 1.

\[
F = \sqrt{F_x^2 + F_y^2 + F_z^2}
\]  

(1)

Where, \(F_x\) is the milling force in the x direction, \(F_y\) is the milling force in the y direction, and \(F_z\) is the milling force in the z direction.

Analyses of the Feed Engagement

The micromilling force under different feed engagement is shown in Fig. 3. It can be seen that the milling force increases gradually with the increase of feed engagement, and the turning point of milling force emerges when the feed engagement is 2.5 μm/z. The morphologies of the chip at different feed engagement are shown in the Fig. 4. It can be seen that when the feed engagement is 1.5μm/z, the tool has only plough effect on the workpiece, and no continuous chips are generated. When the feed engagement is 2.5 μm/z, chip starts to occur. When the feed engagement is larger than 2.5 μm/z, the continuous chip has produced. Therefore, the critical feed engagement value of minimum undeformed cutting thickness (MUCT) in micromilling of oxygen-free copper is about 2.5 μm/z.

![Figure 2. The micromilling force.](image)

![Figure 3. Micromilling force vs. \(f_z\).](image)
(a) $f_z=0.5 \mu m/z$  
(b) $f_z=1.5 \mu m/z$  
(c) $f_z=2.5 \mu m/z$  
(d) $f_z=3.5 \mu m/z$

Figure 4. The chip morphologies.

**Analyses of the Axial Depth of Cut**

The variation trend of milling force under different axial depth of cut is shown in Fig. 5. With the increase of the axial depth of cut, the milling force increases monotonously. It is because that, when the contact area between the workpiece material and the tool increases, the micro end tool requires removing more materials.

**Analyses of the Spindle Speed**

The variation trend of the milling force under different spindle speed is shown in Fig. 6. It shows that with the increase of spindle speed, the milling force decreases in a fluctuating manner. The milling force appears a greater turning point at the spindle speed of 55000 min$^{-1}$. The results show that there is an optimum value of spindle speed when milling OFC.
Analyses of the Radial Depth of Cut

The influence of radial depth of cut on the milling forces is shown in Fig. 7. With the increase of the radial depth of cut, the micromilling force first increases, then decrease and finally rise again. The overall trend of milling force is upward, especially when the radial cutting depth is less than 80 μm.

![Figure 7. Micromilling force vs. αe.](image)

Conclusion

The simulation according to finite element method (FEM) has been carried out for micromilling of the oxygen-free copper C10110. The conclusions drawn through the analyses are as follows. For oxygen-free copper materials, the micromilling force has a turning point with the increase of \( f_z \) due to the size effect in micromilling processes, and the critical undeformed chip thickness is achieved when \( f_z = 2.5 \, \mu m/z \). Micromilling force increases linearly with the increase of \( a_p \), and it presents a fluctuating rise trend with the increase of \( a_e \). With the increase of \( n \), micromilling forces present a fluctuating manner with an overall decrease trend. It suggests that, in the actual micromilling of oxygen-free copper, the \( f_z \) should be chosen bigger than 2.5 μm/z, the \( a_p \) and the \( a_e \) should be selected as a small value to enhance the machining quality and efficiency.

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