Finite element study on chip morphology evolution of Ti6Al4V in micro-milling

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Abstract. Chip is an important index to reflect the quality of machining, and its geometric characteristics such as chip sawtooth degree, sawtooth frequency and radius of curvature are greatly affected by cutting parameters. In order to study and predict the evolution of serrated chip in micro-milling of titanium alloy, finite element analysis software ABAQUS was used to establish the finite element model. Based on elasto-plastic constitutive model, fracture criterion and friction model, the influences of linear velocity and feed per tooth on chip morphology and cutting force were simulated. The relationship between serrated chip formation and cutting force fluctuation is revealed, so as to further explore the chip formation mechanism.

1. Introduction

Titanium alloy has high strength, high rigidity, high temperature resistance, corrosion resistance and other excellent characteristics [1-3], and can maintain excellent performance at low temperatures, widely used in aviation, aerospace, medical and military industries. Due to the poor heat dissipation of titanium alloys, serrated chips produced by adiabatic shear are typical characteristics of titanium alloy machining [4, 5]. In order to select the best milling conditions and increase tool life and surface quality, the cause and effect of chip segmentation in titanium alloys have received important attention.

The periodic change of serrated chip often causes the periodic change of cutting force [6-8], which affects the dimensional accuracy and residual stress of the processed workpiece, aggravates tool wear and reduces tool service life. Both cutting speed and linear velocity are main influence factors of serrated chip formation [9]. When linear velocity increases to a certain degree, chip generated by cutting changes from continuous shape to a serrated shape with evenly spaced adiabatic shear bands, and finally produces discrete chip. High-temperature plastic deformation of the adiabatic shear deformation zone is included in this process, accompanied by the change of equivalent stress, strain and strain rate in the adiabatic shear zone [10-12]. At the same time, the formation of serrated chip also has a certain influence on the cutting force in the cutting machine, and then on the cutting surface quality.

In this paper, the plastic deformation process of serrated chip and the change of cutting force during the milling of titanium alloy are simulated and studied. And the plastic deformation law of the adiabatic shear zone of serrated chip is obtained by comparing the serrated morphology with the changing of cutting force.
2. LAM FEM of Ti6Al4V

2.1. Geometric model

In Abaqus 6.14-4, a two-dimensional model is constructed by layered method, and the whole two-dimensional model is simulated as shown in Figure 1. In the simulation, in order to reduce the amount of mesh as much as possible, chip layer has the largest mesh density. The meshes are all quadrilateral meshes with edges of 0.1μm. There is only one layer of mesh in the separation layer, and the side length is 0.1μm. The rest of the workpiece has a larger grid with a size of 0.3μm.

![Figure 1. 2D simulation model.](image)

The milling tool is simplified to the form of turning tool. Because the machining scale of micro-milling is small, it is simplified to the turning machine, and the cutting depth is small, so the cutting edge radius cannot be ignored in the simulation. When the simulation depth of micro-milling is less than the radius of the cutting edge, the part of the tool involved in milling is a part of the arc edge considering the radius of the cutting edge. Therefore, when it is simplified to turning simulation, the radius of the turning tool's fillet is the radius of the cutting edge at the milling cutter's tip.

2.2. Chip formation mechanism

In the finite element simulation of titanium alloy cutting, arbitrary lagrangian-euler algorithm (ALE) is often used to separate the chip from the workpiece. The method can simulate the machine from initial cutting to steady state, and can divide the mesh according to the mesh distortion and tool-workpiece contact conditions when solving [13-15]. However, the chip separation criteria and chip separation lines still need to be predefined.

However, the formation of chips in actual machining is not entirely dependent on the plastic flow of materials, but also includes shear slip and crack growth. Johnson-cook damage failure criterion is more suitable for laser-assisted micro-milling machining considering material stress, strain rate, temperature and other parameters [5]. The expression as shown in Equation (1).

\[
\tilde{\varepsilon}_{\text{fail}} = \left[ D_1 + D_2 \exp\left( \frac{P}{\sigma}\right) \right] \times \left[ 1 + D_4 \ln\left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_o} \right) \right] \times (1 + D_5 T^*)
\]

(1)

Where, \( \tilde{\varepsilon}_{\text{fail}} \) is the failure strain of the material; \( P \) is the hydrostatic stress (Pa); \( \dot{\varepsilon} \) is the strain rate of the material (s\(^{-1}\)); \( T^* \) is the dimensionless temperature; \( D_1 - D_5 \) are five failure parameters, which can be obtained through experiments.

It is very necessary to use the fracture criterion when the serrated chip is formed in high-speed cutting of Ti6Al4V. The fracture criterion depends entirely on the material properties. Johnson-cook fracture criterion considers strain, strain rate, temperature and stress. The advantage is that the criterion can be determined in tensile and torsion experiments, and the fracture value of each unit can be determined as shown in Equation (2).

\[
D = \sum \frac{\tilde{\varepsilon}}{\dot{\varepsilon}^m}
\]

(2)
Where, $\Delta \bar{e}^{\varepsilon}$ is the increment of the equivalent strain in the integral step; $\bar{e}^{\varepsilon}$ is the failure strain under the current conditions. When $D=1$, the material fails and relevant units are deleted. The failure strain $\bar{e}^{\varepsilon}$ can be obtained as shown in Equation (3).

$$\bar{e}^{\varepsilon} = \left( D_1 + D_2 \exp D_3 \sigma^* \right) \left[ 1 + D_4 \ln \frac{\bar{e}^{\varepsilon}}{\bar{e}} \right] \left[ 1 - D_5 \left( \frac{T - T_0}{T_{melt} - T_0} \right)^m \right]$$

(3)

Where, the failure strain $\bar{e}^{\varepsilon}$ depends on the variable $\sigma^*$, $\bar{e}$, $T$. The dimensionless stress ratios $\sigma^* = \sigma_\mu / \bar{\sigma}$, $\sigma_\mu$ are the average of the three principal stresses, and $\bar{\sigma}$ is the equivalent stress. In this paper, the damage parameters $D1$, $D2$, $D3$, $D4$, and $D5$ of Ti6Al4V in the Literature [16] are -0.09, 0.25, -0.5, 0.0014, and 3.87.

3. Results and discussion
When the feed per tooth is 1μm/z, the simulation results at different linear speeds as shown in Figure 2.

![Figure 2. Chip morphology at different linear speeds in 1μm/z.](image)

In Figure 2, when the feed rate per tooth is fixed, the chip gradually transitions from a continuous chip to a serrated shape as the linear velocity increases. When cutting continues, the sawtooth are regularly distributed on the chip.

When the feed per tooth is 2μm/z, the simulation results at different linear speeds are shown in Figure 3.

![Figure 3. Chip morphology at different linear speeds in 2μm/z.](image)

When the feed amount of each tooth is fixed, with the increase of the linear velocity, the chip is gradually transferred from continuous chip to serrated chip. The chip is still in the section of the chip, and sawtooth is regularly distributed on the chip when the shear continues. When the speed reaches a certain value, the chip is uniformly distributed as a whole.

The serrated chip is characterized geometrically by such parameters as sawtooth degree and sawtooth frequency. The sawtooth degree of chip as shown in Equation (4).

$$G_s = \left( h_1 - h_2 \right) / h_1$$

(4)

Where, $h_1$ is the maximum height of the serrated chip; $h_2$ is the height of the continuous part of the serrated chip, the chip in the simulation is measured and brought into the equation to obtain the sawtooth degree, the results are shown in Table 1.
\( V = 3140 \) mm/s \( (a) \)  
\( V = 3925 \) mm/s \( (b) \)  
\( V = 4710 \) mm/s \( (c) \)  
\( V = 5495 \) mm/s \( (d) \)  
\( V = 6280 \) mm/s \( (e) \)

**Figure 3.** Chip morphology at different linear speeds in 2\( \mu \)m/z.

**Table 1.** Sawtooth degree at different linear speeds.

| Milling speed (mm/s) | 3140 | 3925 | 4710 | 5495 | 6280 |
|----------------------|------|------|------|------|------|
| \( G_s \)            | 0.01 | 0.15 | 0.73 | 0.8  | 0.65 |

The sawtooth frequency is the number of serrated chip produced per unit time, and the sawtooth frequency at different linear speeds are shown in Figure 4 when the feed per tooth is 2\( \mu \)m/z.

**Figure 4.** Sawtooth frequency at different linear speeds.

As shown in Figure 4, with the increase of linear velocity, the radius of chip curvature gradually decreases, and the degree of bending gradually increases, making chip breakage easier. With the increase of linear velocity, the chip is gradually transferred from continuous chip to serrated chip, the serrated degree is gradually increases, and the serrated frequency is also gradually increases. This is
due to the gradual increase of linear velocity and heat, which accumulates at the chip root and cannot be dispersed, forming an adiabatic shear zone, which makes the thermal softening greater than the strain hardening and strain rate hardening, and the chip extrusion deformation forms a sawtooth.

Milling parameters feed per tooth is reflected in turning as cutting depth. In order to study the influence of feed per tooth on machining quality, only one parameter of turning depth is changed to conduct three sets of simulation, and the turning speed is guaranteed to remain unchanged in the simulation process. The chip graph in Figure 2 and Figure 3 are compared one by one according to the same linear velocity. Under the condition of the same online velocity, the chip gradually transitions from continuous chip to serrated chip with the increase of feed per tooth. The radius of chip curvature decreases gradually, that is, the degree of chip bending increases gradually. This is due to the increase of feed per tooth, the thickness of the cutting workpiece increases for a single tool tip, the pressure on the tool tip increases, the contact area between the tool tip and chip also increases, the friction generates more heat, resulting in increased heat accumulation in the shear zone, the maximum shear stress of chip increases, resulting in chip forming a sawtooth.

In two dimensional cutting simulation machine, force signals in two directions, namely the feed direction (X) and cutting thickness direction to (Y), this simulation will mainly study the titanium alloy serrated chip when Y to the change rule of cutting force and the force signal of volatility, and that is associated with chip morphology, chip morphology in order to realize the cutting force prediction. According to the chip morphology in the simulation, the cutting force signal in the simulation process was output and processed. Taking fz=2μm/z per tooth as an example, the –y direction cutting force signal under the line of different linear velocities was shown in Figure 5.

In Figure 5, with the increase of linear velocity, the cutting force fluctuates more and more violently. Comparing the simulation diagram and cutting to, every fluctuation of cutting force corresponding to the formation of a serrated chip, this is to confirm the cutting force and chip corresponding, by observing the chip morphology can predict the fluctuation of cutting force, which can predict the processing quality, generally volatile means cutter cutting force tremor is bigger, machining surface quality is poorer.

4. Conclusions
The cutting simulation of titanium alloy was carried out by ABAQUS, and the chip morphologies and cutting forces under different linear speeds were obtained when the feed per tooth was fz=1μm/z and fz=2μm/z. The conclusions are summarized as follows.
(1) During micro-milling, with the increase of linear velocity, the degree of serration increases gradually in a certain range.

(2) When the linear velocity is constant, the greater the feed per tooth, the greater the degree of chip sawing.

(3) The sawtooth generation of chip is almost the same as the sawtooth force fluctuation, and the generation of each sawtooth is accompanied by a fluctuation of cutting force.

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