

Study on Fracture Mechanism in Micro Ultrasonic Vibration Cutting Process

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Abstract

Using Python language to import Voronoi diagrams into ABAQUS, a two-dimensional microscopic model of vibration cutting of 45 steel is established, and based on this model, the stress changes of grains and grain boundary units on the cutting path are analyzed. The results show that in ultrasonic vibration cutting, the direction of normal stress and shear stress in the grain fracture unit will reverse, and the energy threshold will be reached during multiple impact processes, resulting in failure and deletion; During the impact process, grain boundaries are more prone to advanced failure under normal stress.

Keywords

Vinot Diagram; Microstructure; Vibration Shock.

1. Introduction

As a new special machining technology, vibration cutting is widely used in the field of ultra-precision machining because of its superior cutting performance. Compared with ordinary turning, there are obvious differences in tool motion trajectory and material removal mechanism [1]. In the separation ultrasonic vibration cutting cycle, the tool will be completely separated from the material, making the cutting fluid completely enter the cutting area, improving the lubrication and cooling effect. In addition, the actual cutting angle of the tool, the size and direction of the friction between the tool front and the material will also change [2]. Based on the above cutting characteristics, ultrasonic elliptical vibration cutting can significantly extend the tool life and improve the quality of the cutting surface in the machining of difficult metal materials. In order to realize the application of ultrasonic elliptical vibration cutting technology in ultra-precision machining, it is necessary to accurately reveal the material removal mechanism, which requires more in-depth analysis of ultrasonic elliptical vibration cutting characteristics. Through numerical simulation, Dai Jiangpeng [3] pointed out that the stress value of brittle materials is larger than the stress value of ordinary cutting when the tool is in vibration and impact, the stress wave transmission distance is far, and the tensile limit of the material is exceeded, and the material has advanced microscopic damage, and it is easy to brittle fracture when the tool moves to the cutting point. Ma.L [4] calculated the dynamic stress intensity factor of the vibration grinding zone by numerical analysis method, and proposed that the stress at the point has reached the strength limit before the abrasive particle moves to the breaking point to produce cutting action, and the fracture occurs under the action of the dynamic stress intensity factor. So when the tool (abrasive) really moves to the position, only a small force can be generated to remove the material fracture. Ma.C [5] et al. studied the influence of diamond tools on the critical cutting depth of brittle materials under ultrasonic vibration by conducting groove cutting experiments on brittle materials. It is found that under the condition of ultrasonic vibration, diamond tool can improve the critical cutting depth of brittle material plastic cutting. Liu.C [6] et al. performed molecular dynamics simulations using an improved model to explore the material removal mechanism of monocrystalline silicon under EVC. The results show that the main material removal mechanism changes from extrusion to shear

within one vibration period. In addition, based on the stress analysis, it is found that the formation mechanism of subsurface damage is different in the extrusion and shear stages. Zhenda Wang[7] et al. studied the ultrasonic vibration cutting titanium alloy experiment and numerical simulation, and the results showed that the material removal process of ultrasonic vibration cutting is a "compression shear tension" composite cutting process. For the establishment of micro models, a variety of methods have been developed. The Monte Carlo[8] method was used to establish the micro model at the earliest, which divides the macro model grid into micro size and assigns attributes to the grid randomly by Monte Carlo algorithm. In recent years, with the maturity of microscopic modeling, Zhao Changjie[9] established a microscopic model of cutting titanium alloy and inferred that the position distribution and ratio of grain boundaries affect the fluctuation of cutting force. The relationship between stress and strain of metallographic structure at the phase boundary and the surface roughness after cutting were discussed by Zhao Shize[10] through the numerical simulation of steel cutting in microscopic state. However, the ultrasonic vibration cutting of micro-structures still needs to be studied in detail in terms of its mechanism, stress state, removal method and chip shape.

This paper uses python language to import Voronoi diagram into abaqus to establish a two-dimensional numerical model of micro-vibration cutting. The stress variation of fracture element along the cutting path and the mechanism of advance failure are analyzed by comparing the microcosmic models of normal cutting and vibration cutting. Organization of the Text.

2. Finite Element Model Parameter

2.1. Parametric Modeling

Using ABAQUS/Explicit, Voronoi diagram model is established by using Python language to simulate the microstructure cutting of AISI1045 steel. As shown in Figure 1., the size of the selected simulation model is 1.5mm×1mm, and CPE4RT temperature-displacement coupling unit is used for both the workpiece and the tool. The front Angle of the tool is 10°, the back Angle is 15°, the cutting speed is 500mm/s, the frequency of 20khz and the amplitude of 10um in the cutting direction are added during vibration cutting, and the cutting depth is 0.1mm. A completely fixed constraint is applied to the bottom of the model, and a displacement constraint is given to the left and right sides of the model in the x direction ($U_x=0$). As shown in the picture below:

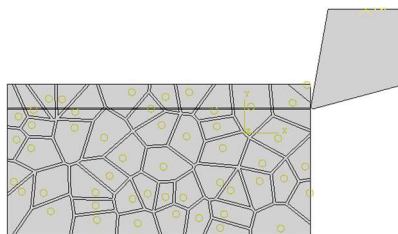


Figure 1. Microscopic cutting model

2.2. Material Constitutive Equation Wo Or more

In this paper, Johnson-cook constitutive model is adopted to consider the influence of strain hardening effect, strain rate and temperature effect. The mathematical equation is as follows:

$$\sigma = (A + B\varepsilon_p^n)(1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}) [1 - (\frac{T - T_0}{T_{melt} - T_0})^m] \quad (1)$$

A:Yield strength under quasi-static conditions;

B:Strain hardening parameter;

ϵ_p : Equivalent strain;

n:Hardening index;

C:Strain rate strengthening parameter;

$\dot{\epsilon}$:Equivalent strain rate;

ϵ_0 :Reference strain rate of the material;

T_0 :Room temperature coefficient;

T_{melt} is Material melting point;

m :Thermal softening parameter.Johnson-Cook's failure model is used under the premise of considering stress triaxial degree, strain rate and temperature for material failure:

$$\omega = \sum \Delta \bar{\epsilon}^{pl} / \bar{\epsilon}_f^{pl}$$

ω is Failure parameter;

$\Delta \bar{\epsilon}^{pl}$ is Equivalent plastic strain increment;

$\bar{\epsilon}_f^{pl}$ is Failure strain,When $\omega > 1$, the material begins to fail and the unit is deleted.

the expression of $\Delta \bar{\epsilon}^{pl}$ is:

$$\Delta \bar{\epsilon}^{pl} = [D_1 + D_2 x p(D_3 \sigma^*)] + (1 + D_4 \ln \bar{\epsilon}_0^*) (1 + D_5 T^*) \tag{2}$$

D_1, D_2, D_3, D_4, D_5 is parameter

$\sigma^* = p / \sigma_{ep}$,

p is the hydrostatic pressure,

σ_{ep} is Equivalent stress;

ϵ_0 is the ratio of the equivalent strain rate to the reference strain rate;

$T^* = (T - T_0) / (T_{melt} - T_0)$.

Mechanical properties of materials and jc damage constitutive parameters are shown in Table 1. and Table 2.

Table 1. Mechanical properties parameter table

Material parameter	pearlite	ferrite
Density(kg/m ³)	7850	7880
Modulus of elasticity (GPa)	220	190
Poisson's ratio	0.3	0.3
Specific Heat Capacity (J/(kg·°C-1))	463	448
Thermal conductivity(W·m-1·°C-1)	55	55
Coefficient of expansion	12	12

Table 2. J-C damage parameters

Materials	A(MPa)	B(MPa)	C	n(W·m·1·°C ⁻¹)	m
Pearlite	750	593	0.011	0.33	1.1
Ferrite	782	498	0.028	0.28	1.86

2.3. Knife-chip Contact Properties

In order to obtain a reliable and realistic simulation, the setting of the contact properties between the tool and the workpiece is very important, and there is a complex friction between the front tool face and the workpiece during the cutting process. In this paper, the modified Coulomb bonding and sliding friction model is used to simulate the contact properties between the tool and the workpiece, and the friction properties are expressed as:

$$\begin{cases} \tau = \mu\sigma_n (\mu\sigma_n < \bar{\tau}_{max}) \\ \tau = \bar{\tau}_{max} (\mu\sigma_n \geq \bar{\tau}_{max}) \end{cases} \quad (3)$$

τ Frictional stress;

σ_n : Normal stress;

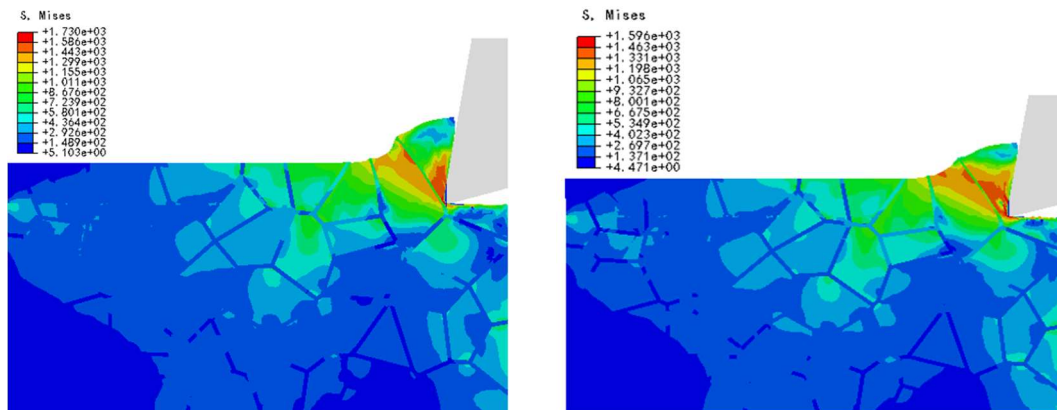
$\bar{\tau}_{max}$ is Ultimate shear stress,

μ Is the friction coefficient, the value is 0.2.

According to the friction characteristics of cutting, the normal contact is defined as hard contact, tangential contact as penalty friction, and the contact property between the tool and the workpiece is selected as face-surface contact.

3. Finite Element Simulation Process and Results

3.1. Mises Stress Analysis



(a) General cutting stress nephogram (b) Vibration cutting stress cloud map

Figure 2. Comparison nephogram of Mises stress between normal cutting and vibration cutting

Figure 2(a) shows that under the continuous extrusion of the tool, the workpiece material formed a large area of accumulation on the front tool surface, and the Mises stress of the workpiece was concentrated in the first deformation zone and the contact surface between the front tool surface and the workpiece, reaching the maximum value of 1730Mpa. Due to poor plasticity of pearlite grains, the whole internal grain will be subjected to great stress, and ferritic

materials in the cutting process, due to good plasticity, produce great plastic deformation and by the surrounding second phase pearlite extrusion. In turn, from the point of view of a single grain, it will produce a larger deformation than the pearlite grain, reflecting the overall shape of the chip, which will produce a similar sawtooth chip generation. In the process of vibration cutting Figure 2(b), the separation process greatly reduced the extrusion time of the tool on the cutting layer and the average value of the cutting force during the cutting process, thus reducing the extrusion of the front tool on the cutting shoulder, and the maximum Mises stress was reduced to 1596Mpa.

3.2. Study on Fracture of Grain

In order to analyze the fracture of pearlite and ferrite under ultrasonic vibration cutting, the grain and grain boundary elements at the peak tool speed were selected on the cutting path for analysis. Figure 3 shows the stress states of the fractured grain elements under different cutting states.

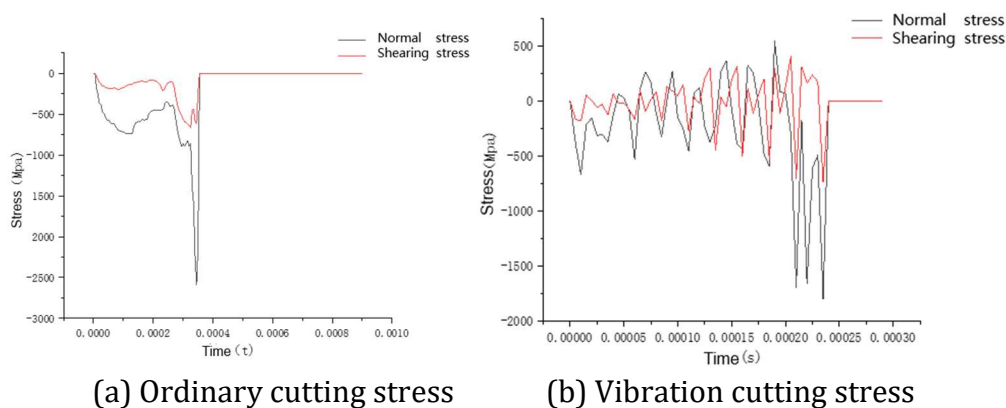


Figure 3. Comparison of normal stress and shear stress of grain elements

Figure 3(a) shows the curve of shear stress and normal stress of grain element with time under ordinary cutting. It can be seen from the figure that both shear stress and normal stress first increase and then decrease in the negative direction. That is, at 0.35 μ s, that is, when in contact with the tip of the tool, the stress reaches the maximum normal stress of -2611Mpa, the maximum shear stress of -680Mpa, and then the fracture fails. Figure 3(b) shows the stress curve under vibration cutting. With the increase of time, the fluctuation degree of the curve increases. The reason is that the tool is in high frequency vibration, the fracture node is in a state of pressure when the cutter is fed, and the shear stress and normal stress values are negative. It can be seen from the figure above that the maximum shear stress and normal stress of the fracture joint are -1800Mpa and -700Mpa. Compared with ordinary cutting, the normal stress decreases significantly and the shear stress increases slightly. JC fracture adopts the fracture energy method to control the failure deletion of the unit, and the unit fails when the energy reaches the extreme value. Before breaking, the unit has been damaged in the first two shocks, and can be removed by failure at a relatively low stress state when cutting again.

3.3. Fracture Study at Grain Boundary

The following figure shows the stress states of broken grain boundary elements under different cutting states. Figure 4(a) shows the change curve of shear stress and normal stress of grain boundary element with time under ordinary cutting. The law is the same as that of grain cutting, both shear stress and normal stress increase first in the negative direction and then decrease. That is, at 6 μ s, the stress reaches the maximum normal stress of -2200Mpa and the maximum shear stress of -450Mpa when in contact with the tip of the tool, and then breaks and

fails. Figure 4(b) shows the stress curve under vibration cutting. It can be seen from the figure that during the vibration process, under the impact effect, the normal stress curve changes significantly. In the first high-speed impact, the impact and grain unit extrusion reach the maximum value of -680 mpa, while the shear stress is distributed in the range of -100 mpa ~200Mpa, and the change of shear force under the impact effect is not obvious. After multiple impacts, the energy accumulates to the threshold value, resulting in advanced fracture failure, as shown in Figure 5:

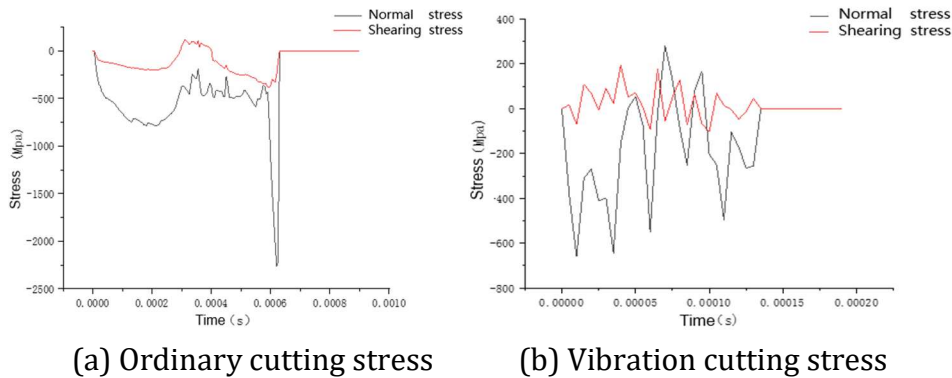


Figure 4. Comparison of normal stress and shear stress of grain boundary elements

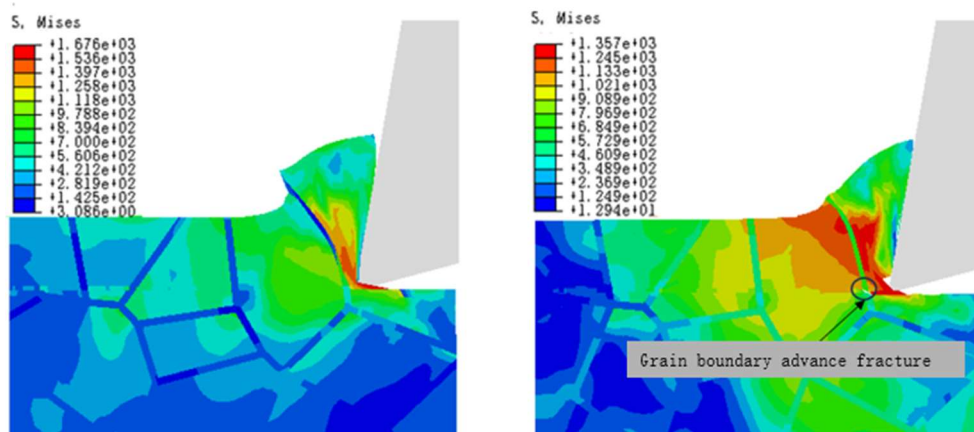


Figure 5. Advanced failure of grain boundary elements deleted Mises diagram

4. Conclusion

Using python language to establish a two-dimensional microscopic model of vibration cutting 45 steel. The grain and grain boundary were cut with pearlite and ferritic materials. The two-dimensional microscopic numerical model under normal and vibration cutting conditions is used as the comparison data. By analyzing the stress of grain boundaries and grains along the fracture path, the following conclusions are obtained:

- (1) Extreme normal stress of the fractured grain unit decreases by 31% and the shear stress increases slightly in the process of vibration cutting, but the direction of both grain units will reverse in the process of tool withdrawal, and finally reach the energy threshold fracture under the effect of multiple shocks.
- (2) Grain boundary is more prone to premature fracture under normal stress. Due to the periodic impact effect, grain boundary elements are more likely to be destroyed under multiple cumulative normal stresses. It is not caused by the extrusion effect of the tool under ordinary cutting conditions.

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