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PREDICTION OF TEMPERATURE AND STRESS DISTRIBUTION DURING MICRO-CUTTING OF TI-6AL-4V

Lu Dong[1] Li Jianfeng[1] Rong Yiming[2] Sun Jie[1] Wang Zhongqiu[1]

[1]School of Mechanical Engineering, Shandong University, Jinan, China

[2]Department of Mechanical Engineering, Worcester Polytechnic Institute, Worcester, USA

ABSTRACT

A finite element method (FEM) for predicting the temperature and stress distribution in micro-cutting of Ti-6Al-4V is presented. The flow stress of Ti-6Al-4V is taken as a function of strain, strain rate and temperature in order to reflect realistic behavior in machining process. Diamond cutting tool is used. From simulation, cutting force, thrust force, cutting temperature and distribution of cutting temperature and stress are obtained. The effects of cutting speed and uncut chip thickness on the maximum temperature and maximum shear stress are analyzed and size effect is observed. The simulation results show that in micro-cutting of Ti-6Al-4V the maximum temperature locates on the shear plane. And the maximum shear stress locates on the stick region. The maximum temperature decreases as the uncut chip thickness decreases, and it increases with an increase in cutting speed. The maximum shear stress increases as the uncut chip thickness decreases, and it decreases with an increase in cutting speed.

Keywords: micro-cutting, stress distribution, size effect, FEM

INTRODUCTION

Highly-accurate micro-components are increasingly demanded for various industries, such as aerospace, biomedical, electronics, communications, and automotive. Many common methods of manufacturing micro-components have been based on the lithography processing techniques commonly used in semi-conductor industry, where silicon materials are photo-etched through chemical and dry processes. Some researchers have investigated the feasibility of using fabrication processes, such as laser, ultrasonic, ion beam, and micro-electro discharge machining methods, to manufacture viable micro-components [1]. However these methods are often slow, limited to a few silicon-based materials, and essentially with planar geometrics. Mechanical micro-cutting is capable of fabricating three-dimensional features with reasonably low cost. But the fundamental mechanics of mechanical micro-cutting is not well understood.

Experimental method has been used to investigate the mechanics of micro-cutting. The effects of cutting conditions on the machining forces, chip geometry, surface roughness, specific energy, shear angle and mean friction coefficient have been studied in orthogonal micro- and nano-scale cutting of Al7075-T6 [2]. The results indicate that when the uncut chip thickness is greater than the cutting edge radius of the tool (60~100 nm) the cutting force exhibits an approximately linear relationship with the uncut chip thickness. But when the uncut chip thickness is smaller than the edge radius of the tool, a non-linear variation in the cutting forces is observed and the size effect in the specific cutting energy is also non-linear. The feasibility of manufacturing annealed steel molds for micro component production using ultra fine grain tungsten carbide end mills are investigated and it was reported that the cutting tools represented the present bottleneck in the ongoing development of micro cutting technology [3]. A static chip formation model has been developed for micro-cutting of brass [4]. This model is able to account for the coupled minimum chip thickness and edge-radius effects.

At the same time, the finite element method was used to investigate the mechanics of micro-cutting. A finite element model was developed to predict the stress and temperature distribution in micro cutting of oxygen-free-high-conductivity copper [5]. The results indicated that the temperature was an important factor in micro cutting due to its influence on the flow stress. A train gradient plasticity-based finite element model was presented to predict the size effect in orthogonal cutting of aluminum alloy Al5083-H116 [6]. The analysis indicated that the strain gradient plasticity based model of orthogonal micro-cutting was able to capture the size effect in specific cutting energy. The finite element method was also used to analyze the orthogonal micro-cutting with the effect of the tool edge radius [7]. The results showed a good agreement with experimental cutting of copper with a sharp diamond tool. The minimum chip thickness of steel was determined by using the finite element method and it was reported the critical chip thickness was 0.2 and 0.3 times of the edge radius for pearlite and ferrite respectively.

However, these studies involved only the workpiece materials that are soft, ductile and easy to be machined. There is a need for investigations of micro-cutting of difficult-to-machine materials. Titanium and its alloys are considered as difficult-to-machine materials because of their low thermal conductivity, high chemical reactivity, and low modulus of elasticity. The workpiece material chosen for this study is Ti-6Al-4V, which is often used in aerospace and biomedical industries. The micro-cutting of Ti-6Al-4V with a diamond tool was simulated with Third Wave Systems AdvantEdge machining simulation software.

MATERIAL MODELING

The flow stress is mostly influenced by temperature, strain, strain rate, and other factors. An accurate and reliable flow stress model is necessary to represent workpiece constitutive behavior during the cutting process. The material behavior is modeled by using the constitutive equation [9],

$$\left(1+\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0^p}\right)=\left(\frac{\bar{\sigma}}{g\left(\varepsilon^p\right)}\right)^{m_1}, \text{ if } \dot{\varepsilon}^p \le \dot{\varepsilon}_t \qquad (1)$$

$$\left(1+\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0^p}\right)\left(1+\frac{\dot{\varepsilon}_t}{\dot{\varepsilon}_0^p}\right)^{m_1/m_2-1}=\left(\frac{\bar{\sigma}}{g\left(\varepsilon^p\right)}\right)^{m_2}, \text{ if } \dot{\varepsilon}^p > \dot{\varepsilon}_t \qquad (2)$$

where $\bar{\sigma}$ is the effective Mises stress, g is the flow stress, ε^p is the accumulated plastic strain, $\dot{\varepsilon}_0^p$ is a reference plastic strain rate, m_1 and m_2 are low and high strain rate sensitivity exponents, respectively, and $\dot{\varepsilon}_t$ is the threshold strain rate which separates the two regimes.

And a power hardening law with linear thermal softening is given [9],

$$g=\left[1-\alpha\left(T-T_\circ\right)\right]\sigma_0\left(1+\frac{\varepsilon^p}{\varepsilon_0^p}\right)^{\frac{1}{n}} \qquad (3)$$

where n is the hardening exponent, T is the current temperature, $T_\circ$ is a reference temperature, α is a softening coefficient, and σ_0 is the yield stress at $T_\circ$.

FRICTION FORCE ON THE CHIP-TOOL INTERFACE

To obtain a reliable and realistic simulation result of metal cutting, it is essential to investigate the interaction between the cutting tool and the chip. The friction force is strongly influenced by cutting speed, contact pressure, and cutting temperature. Zorev's model [10] reveals two distinct regions on the chip-tool interface sliding region and sticking region. The normal and frictional shear stress distribution at the chip-tool interface is shown in Fig.1 [10].

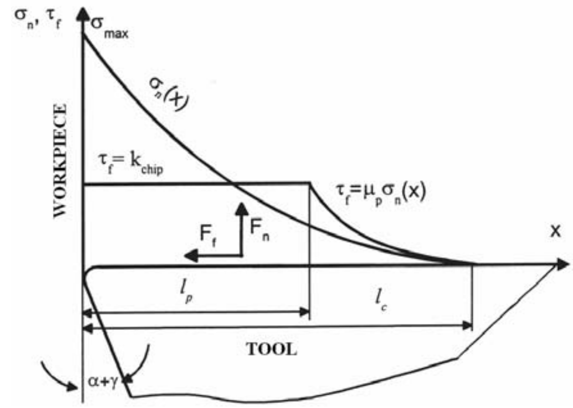


Fig.1 Curves representing normal (σ_n) and frictional stress (τ_f) distribution on the to rake face [10]

From the tip of the tool up to a point, frictional stress is considered constant in a sticking region. After this point, frictional stress decreases on the tool rake face in a sliding region where Coulomb's friction law can be used. This can be represented as follows.

$$\tau_f=\mu\sigma_n \text{, when } \mu\sigma_n < k_{chip} \text{ (sliding)} \qquad (4)$$

$$\tau_f=k \text{, when } \mu\sigma_n \ge k_{chip} \text{ (sticking)} \qquad (5)$$

where τ_f is the frictional stress, σ_n is the normal stress, μ is the coefficient of friction, and k_{chip} is the shear stress of the chip material.

The constant friction stress k_{chip} in the sticking region and constant friction coefficient μ in the sliding region can be obtained from the friction model [11]. Define the constant friction coefficient in sliding region as follows,

$$\mu_p=F_f/F_n \qquad (6)$$

$$F_f=F_c\sin\alpha+F_t\cos\alpha \qquad (7)$$

$$F_n=F_c\cos\alpha-F_t\sin\alpha \qquad (8)$$

where F_f is the friction force on the tool rake face, F_n is the normal force on the tool rake face, α is the rake angle of cutting tool, F_c is the cutting force, and F_t is thrust force.

Define a variable friction coefficient in sticking region as follows,

$$\mu_i=k_{chip}/\sigma_n \text{, until } \mu_i=\mu_p. \qquad (9)$$

where k_{chip} is the shear stress of the chip material and σ_n is the normal stress.

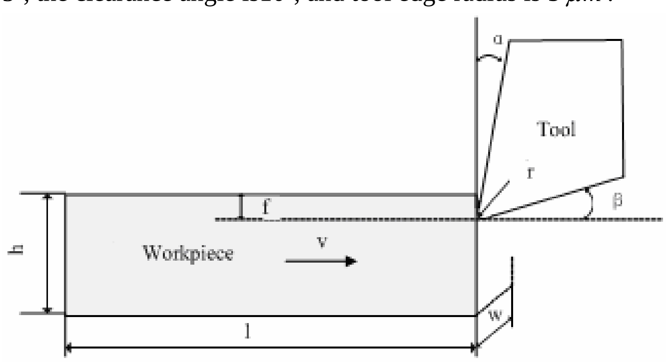
μ_i and μ_p can be input into the finite element model and simulation cutting process. The simulated cutting force, thrust force are compared with the test results of cutting force and thrust force. If the simulated forces agree with the measured forces, a list of μ_p and k_{chip} are output as results. If the simulated forces do not agree with the measured forces, then calculate k_{chip} with modified μ_p and go on with next loop of simulation.

FINITE ELEMENT MODEL DEVELOPMENT

Two finite element formulations have been traditionally used in modeling of metal cutting: the Lagrangian formulation and the Eulerian formulation. In Eulerian approach, the mesh is fixed spatially and the material flows through the mesh. Eulerian approach is suitable to analysis the steady state of cutting process. But it cannot be used to analyze neither transition from initial to steady state cutting process nor chip geometry because it is unable to simulate free surface conditions. Experimental work is often necessary to determine the chip geometry and shear angle. In Lagrangian approach, the mesh follows the material. It can be used to simulate the transition from initial to steady state cutting and chip geometry. Before the cutting simulation, the chip separation criteria must be defined. And adaptive remeshing is used to alleviate element distortions.

In this paper, the Lagrangian approach is applied. A schematic of the tool-workpiece configuration is shown in Fig.2. Simulations were performed with Third Wave Systems AdvantEdge machining simulation software. AdvantEdge [12] is an explicit dynamic, thermo-mechanically coupled finite element model specialized for metal cutting. The element topology used is a six-node quadratic triangle element with three corner and three midsize nodes. Continuous adaptive remeshing is used to correct the problem of element distortion due to high deformations.

In the simulation, the length of the workpiece is 5mm, the height of the workpiece is 2mm, and width of cut is 1mm. The cutting tool material is single point diamond. The rake angle is 5^0, the clearance angle is10^0, and tool edge radius is 5 μm .



f: uncut chip thickness; v: cutting velocity; w: width of cut;
h: height of workpiece; l: length of workpiece;
r: tool edge radius; α : rake angle; β : clearance angle.

Fig.2 Schematic of orthogonal cutting model

TEMPERATURE AND STRESS ANALYSIS

Orthogonal cutting simulations were performed with different depth of cut and cutting speed. The temperature and stress distribution were predicted and the effects of depth of cut and cutting speed were analyzed.

Temperature and Stress Distribution

Fig.3 shows the temperature distribution in the chip and tool. In conventional cutting, the maximum temperature is located on the chip-tool contact surface. However, in micro-cutting the maximum temperature is located on the shear plane. Because of Ti-6Al-4V has low thermal conductivity, about 6 to 7 W/m.K (vs. 167W/m.K of aluminum alloys and 1600 W/m.K of diamond).The low thermal conductivity makes the heat difficult to transfer outside the deformation zone during the chip formation. The high temperature is confined in the deformation zone, softens the workpiece, generates even larger deformation and heat, and further increases the temperature in a narrow band of deformation zone which is called 'shear plane'. In micro-cutting the contact area between the chip and tool is small and the conductivity of the cutting tool is larger than the workpiece. The majority heat on the chip-tool contact surface is taken away by the cutting tool.

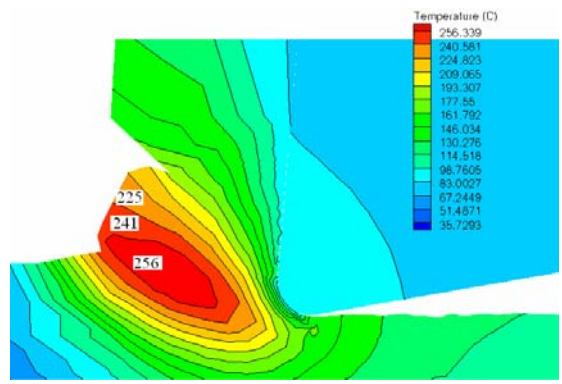


Fig.3 Contours of predicted temperature for cutting speed 30m/min, uncut chip thickness 8 μm

Fig.4 and Fig.5 show distribution of the Maximum shear stress and Mises stress. The maximum shear stress of workpiece exhibits on the sticking region. The maximum shear stress of cutting tool exhibits on the tool edge. Mises stress distribution of workpiece and cutting tool is similar with the maximum shear stress.

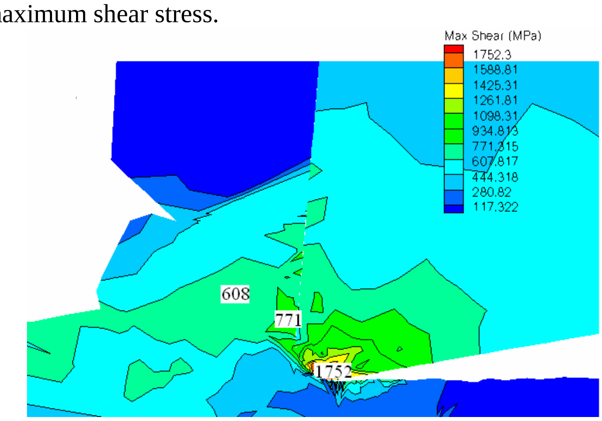


Fig.4 Contours of predicted maximum shear stress for cutting speed 30m/min, uncut chip thickness 8 μm

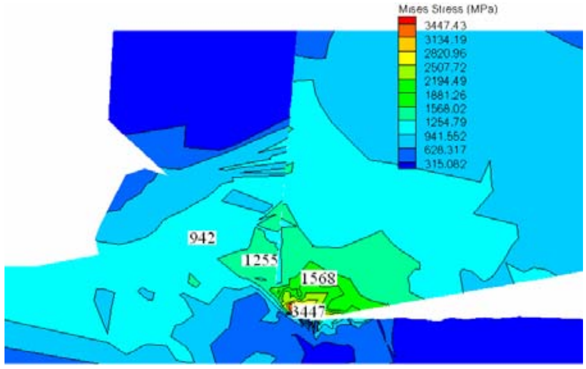


Fig.5 Contours of predicted Mises stress for cutting speed 30m/min, uncut chip thickness 8 μm

Effect of Depth of Cut

For one cutting speed 150m/min four uncut chip thickness are carried out 10 μm , 8 μm , and 7 μm .Table 1 shows the simulated results. As uncut chip thickness decreases, the cutting force, thrust force, and the maximum temperature decrease but the maximum shear stress increases.

Table 1 Simulation results for various depths of cut

Feed (μm)	10	9	8	7
F_c (N/mm)	35-37	32-34	30-32	29-31
F_f (N/mm)	26-29	24-25	22-24	19-21
T_{max} (℃)	474	470	467	463
τ_{max} (MPa)	557	565	574	586
u_t (MPa)	3500-3700	3556-3778	3750-4000	4143-4229

Effect of Cutting Speed

For one uncut chip thickness 8 μm three cutting speed are carried out 30m/min, 90m/min, and 150m/min. Table 2 shows the simulated results. As the cutting speed increases, the maximum temperature increases, but the cutting force, thrust force and maximum shear stress decrease.

Table 2 Simulation results for various cutting speed

Cutting speed (m/min)	30	90	150
F_c (N/mm)	38-44	33-35	30-32
F_f (N/mm)	28-30	24-26	20-24
τ_{max} (MPa)	771	623	574
T_{max} (℃)	286	406	467

SIZE EFFECT ANALYSIS

In micro-cutting, the size effect is typically characterized by a non-linear increase in the specific cutting energy as the uncut chip thickness is decreased. The specific cutting energy, which represents the energy required to remove a unit volume of workpiece, is calculated from the cutting force, uncut chip thickness, and width of cut,

$$u_t = \frac{F_c}{fw} \quad (10)$$

Where u_t is the specific cutting energy, F_c is the cutting force, f is the uncut chip thickness and w is the depth of cut.

For one cutting speed 150m/min four uncut chip thickness 10 μm , 8 μm , and 7 μm are carried out. Simulation results of u_t are show in table 1. And the variation of specific cutting energy with uncut chip thickness is shown in Fig. 6.

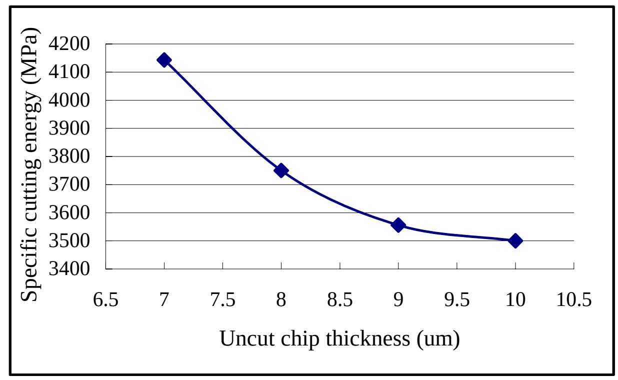


Fig.6 Variation of specific cutting energy with uncut chip thickness

CONCLUSION

In this paper, the temperature and the stress distribution in micro-cutting of Ti-6Al-4V are analyzed by finite element method. The diamond cutting tool with rake angle 5^0, clearance angle 10^0, and tool edge radius 5 μm is used. The flow stress of workpiece material is taken as a function of strain, strain rate and temperature, to reflect a realistic behavior in the micro-cutting process. The following conclusions can be drawn from the simulation:

1. Different from conventional cutting, in micro-cutting the maximum temperature is located on the shear plane. For the same cutting speed the maximum temperature decreases as the uncut chip thickness decreases. And for the same uncut chip thickness the maximum temperature increases as the cutting speed increases.

2. The maximum shear stress of workpiece exhibits on the sticking region. For the same cutting speed the maximum shear stress increases as the uncut chip thickness decreases. And for the same uncut chip thickness the maximum shear stress decreases as the cutting speed increases.

3. For the same uncut chip thickness the cutting force and thrust force decrease as the cutting speed increases. For the same cutting speed the cutting force and thrust force decrease as the uncut chip thickness decreases but the specific cutting energy increases. And the size effect is observed.

4. To improve the cutting efficiency, high cutting speed is necessarily used in micro-cutting.

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