 Simulation of ultrasonic vibration cutting performance of GH2132 superalloy

Hua Guo 1,2, Chuangchuang Zhou 1, Kaikai Wang 2 and Zhen Jiang 1,*

1 School of Mechatronics Engineering and Automation, Shanghai University, Shanghai, China
2 Shanghai Technical Institute of Electronics & Information, Shanghai, China

*Corresponding author e-mail: zhjiang@shu.edu.cn

Abstract. The vibration amplitude, vibration frequency, cutting speed, feed rate and cutting thickness in ultrasonic vibration cutting have an important influence on the cutting temperature and the cutting force. Through the mathematical model and finite element simulation, the suitable vibration frequency is obtained. The vibration frequency is used to further simulate the effect of the change in feed rate on the cutting temperature and cutting force.

1. Introduction

Ultrasonic vibration cutting technology is a kind of precision machining. Due to the discontinuity of machining, the workpiece and the tool can be contacted and separated during the cutting process, which can reduce the cutting heat during cutting, reduce the cutting force, and reduce the surface roughness. Ultrasonic vibration turning is a processing method of applying ultrasonic vibration to a tool or workpiece based on the relative movement of the tool and the workpiece in ordinary turning [1, 2]. Ultrasonic vibration turning can be divided into longitudinal vibration turning, lateral vibration turning, feed vibration turning and compound vibration turning according to the direction in which vibration is applied. In this study, the longitudinal vibration turning method is adopted, so that the tool obtains ultrasonic vibration mechanical vibration of certain amplitude, thereby realizing ultrasonic vibration turning processing.

GH2132 (0Cr15Ni26MoVTi2B) is an age-hardening iron-based superalloy with good thermal stability and thermal strength, good plasticity and machinability. GH2132 has stable structure and performance when working at 650 °C for a long time. It is a new type of low expansion superalloy that can be used in the manufacture of aerospace turbine engine components. GH4169 is a nickel-based deformed superalloy with high strength, high plasticity, low thermal conductivity and severe work hardening. It has a large cutting force, high cutting temperature and low tool life during cutting. It is a typical material difficult to process. At present, the research on ultrasonic vibration cutting of superalloys mainly focuses on nickel-based superalloy GH4169 [3]. There are very few related researches on iron-based superalloys GH2132. First, the GH4169 and GH2132 are simulated by ultrasonic vibration cutting at different amplitudes to find the optimal amplitude. Then, using this amplitude and a certain vibration frequency, the characteristics of the cutting performance of GH2132 under different feed rates and cutting speeds were studied [4, 5].
2. Establishment of simulation model

2.1. Geometric model
The influence of cutting tool deformation and vibration to the simulation results were neglected in the finite element model, the cutting tool was assumed as a rigid body, and the whole simulation was two-dimensional analysis. Four node plane strain thermal coupling unit was used in meshing the workpiece and three node plane strain thermal coupling unit was used in meshing the tool. The meshes of cutting tool and workpiece were dense near the cutting area whereas others were relatively sparse. The ultrasonic vibration turning machining system is composed of an ultrasonic vibration system and a lathe. The ultrasonic vibration system mainly includes an ultrasonic generator, an ultrasonic transducer, an ultrasonic horn and a cutter system. Fig. 1 shows its working principle diagram. GH2132, GH4169 were used as the workpiece materials, The material of the cutting tool in the simulation was carbide-k.

![Schematic of longitudinal ultrasonic vibration turning.](image)

2.2. Constitutive model
During the cutting process, high temperature and large strain result in elastoplastic deformation of the material. The distribution of strain, strain rate and temperature in each part of the shear region is not uniform, so the constitutive equation that can reflect the influence of strain, strain rate and temperature on the flow stress of the material is very important in the simulation. Johnson-Cook (JC) model can describe the thermal viscoplastic deformation behavior of materials at high strain rates, so this constitutive model is used to describe the material yield flow behavior [6]:

\[
\sigma = \left[ A + B e_p^m \right] \left[ 1 + C \ln \left( \frac{\dot{e}_p}{\dot{e}_o} \right) \right] \left[ 1 - \left( \frac{T - T_c}{T_m - T_c} \right)^n \right]
\]  

(1)

With respect to Eq. (1), Johnson-Cook (J-C) flow stress model was utilized to represent the behavior of workpiece material during chip formation. A, B, C, m and n are the constants determined by the material itself, \( e_p \) is the equivalent strain, \( \dot{e}_p \) is the plastic strain rate, \( \dot{e}_o \) is the reference of plastic strain rate, \( \sigma \) is the equivalent flow stress, respectively, and the variables \( T \) is the environment temperature, \( T_m \) is melting point, \( T_c \) is reference temperature.

The work of workpiece plastic deformation is continuously converted into heat in the cutting process, and the conversion ratio is \( \mu \) (heat generation coefficient), then the heat conduction equation can be expressed as:
\[
\lambda \frac{\partial^2 T}{\partial y^2} - \rho c \frac{\partial T}{\partial y} + \mu \tau' = \rho c \frac{\partial T}{\partial t}
\]  
(2)

where \( \lambda \) is heat transfer coefficient; \( \rho \) is material density; \( c \) is heat capacity; \( \mu \) is coefficient of Taylor-Quinney.

In general, heat transfer is often negligible during high-speed cutting, and it is believed that temperature is constant in the shear zone under steady cutting state.

2.3. Chip separation criteria

In the process of metal cutting, the cutter removes the material to form chips by shearing action. The separation of chip and workpiece was realized by incessant hypermesh in the simulation. The local chip grids are distorted under high temperature and high strain rate conditions. When the distortion reaches a certain extent, the grid begins to be deleted and redvided to achieve chip separation from the workpiece [7]. In order to implement this process in the process, it is necessary to set the separation criteria for the swarf. The separation criterion of chip is shown in equation (3).

\[
D = \sum \frac{\Delta e_{\text{f}}}{e_{\text{fr}}}
\]  
(3)

where \( D \) is dimensional-accumulated damage; \( \Delta e_{\text{f}} \) is transient strain increment; \( e_{\text{fr}} \) is transient strain damage increment. If \( D > 1 \), material failure, chip separated from the workpiece.

2.4. Friction model

The finite element simulation used the Coulomb friction model [8], which is shown in equation (4).

\[
\tau_i = \mu \sigma
\]  
(4)

where \( \tau_i \) is friction shear stress; \( \sigma \) is normal stress; \( \mu \) is friction factor, \( \mu = 0.5 \).

2.5. Simulation parameters

Ultrasonic vibration cutting of GH4169 superalloy has been extensively studied. Through this set of experimental simulations, the appropriate ultrasonic vibration amplitude is found as a parameter for the GH2132 ultrasonic vibration cutting simulation. As shown in Table 1, the cutting parameters for the cutting simulation of GH4169 and GH2132 superalloy.

| Experiment number | Ultrasonic amplitude (\( \mu m \)) | Ultrasonic frequency(KHz) | Feed rate(mm/r) | Cutting speed(m/min) | Cutting thickness(mm) |
|-------------------|-----------------------------------|---------------------------|-----------------|----------------------|----------------------|
| a                 | 4                                 | 20                        | 0.1             | 25                   | 0.1                  |
| b                 | 8                                 | 20                        | 0.1             | 25                   | 0.1                  |
| c                 | 12                                | 20                        | 0.1             | 25                   | 0.1                  |
| d                 | 16                                | 20                        | 0.1             | 25                   | 0.1                  |
| e                 | 20                                | 20                        | 0.1             | 25                   | 0.1                  |
3. Results and discussions

3.1. Cutting simulation when amplitude changes

As shown in Fig. 2, the cutting temperature diagram obtained according to the parameters in Table 1 (the experimental results of the four groups of parameters a, b, c, and d are listed in the figure) can be seen from Fig. 2. As the vibration amplitude increases, the cutting temperature gradually increases.

![Figure 2. Relationship between ultrasonic amplitude and cutting temperature.](image)

It can be seen from Fig.3 that Force-X gradually decreases while the ultrasonic vibration amplitude increases from 4 μm to 16 μm, and Force-Y gradually increases, but the increase is slow. Considering the simulation results of the amplitude diagrams 3 and 4, the cutting force and the cutting temperature of the vibration cutting are small when the amplitude is 8-12 μm.
3.2. Cutting simulation of GH2132 when the feed rate changes

The GH2132 was subjected to cutting simulation using the parameters of Table 2. As shown in Fig. 4 and Fig. 5, when the amplitude is 12 μm, the change of the cutting temperature and the cutting force of the GH2132 superalloy as the feed rate increases. From the simulation results, the cutting temperature increases gradually with the increase of the feed rate, the cutting force in the X direction increases gradually, and the cutting force in the Y direction to which the ultrasonic vibration is applied does not change much, indicating that the ultrasonic vibration can effectively reduce the cutting force.

Table 2. Parameters of GH2132 cutting simulation

| Experiment number | Ultrasonic amplitude (μm) | Ultrasonic frequency(KHz) | Feed rate(mm/r) | Cutting speed(m/min) | Cutting thickness(mm) |
|-------------------|---------------------------|---------------------------|-----------------|----------------------|----------------------|
| a                 | 12                        | 20                        | 0.10            | 25                   | 0.1                  |
| b                 | 12                        | 20                        | 0.15            | 25                   | 0.1                  |
| c                 | 12                        | 20                        | 0.20            | 25                   | 0.1                  |
Figure 4. GH2132 increases the cutting temperature with the feed rate when the amplitude is 12μm.

Figure 5. GH2132 increases the cutting force with the feed rate when the amplitude is 12μm.

4. Conclusion
Through mathematical model and finite element simulation, the changes of cutting temperature and cutting force of GH4169 and GH2132 superalloys were studied when the amplitude of ultrasonic vibration was changed. The cutting temperature and cutting force were small when the ultrasonic amplitude was 8-12 μm. Further simulation using the vibration frequency of 12 μm found that as the feed rate increases, the cutting temperature increases and the cutting force increases.
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