Simulation Analysis on The Influence of Temperature and Stress in The Plastic Processing of Crystal Germanium

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Abstract: Crystal germanium has the characteristics of high hardness and brittle quality. It is a common material for infrared optical parts. In order to explore the mechanical properties of germanium crystals in plastic processing and the influence of temperature on cutting, FEM software was used to conduct micro cutting simulation on the ultra-precision turning process of germanium crystals, and the cutting force, temperature and cutting energy in the cutting process were analyzed. The results show that the main cutting force and cutting resistance decrease with the increasing of the temperature. By calculating the unit cutting force and the unit cutting resistance, the change of cutting energy is reflected indirectly. By means of normalization of cutting force, the specific gravity of stress and temperature to the cutting process at different temperatures is obtained.

1. Introduction

Germanium crystal is an important infrared optical crystal material, it has the characteristics of high brittleness and low fracture toughness, and it is easy to cause surface wear or damage during processing. At present, single point diamond ultra-precision cutting (SPDT) is the main method for machining hard and brittle materials [1-2]. Therefore, a new and improved method-heating the germanium material to thermally soften it, and then perform plastic processing on the thermally softened surface to improve the cutting performance of germanium [3]. In the process of germanium plastic cutting, temperature and stress are two important factors that affect the surface finish of the machined. Therefore, studying the comprehensive influence of temperature and stress during the machining process is of great significance to improve the machining quality.

FEM software was selected for this simulation. Since the processing method used is micro-cutting, the thermal effect produced is also on a microscopic scale. In this case, the simulated workpiece is a germanium material, and the thermal softening curve based on reference [4] is used to adapt the thermal softening behavior. The material model uses the Drucker-Prager yield criterion to determine the effect of pressure on the material, given the different initial temperatures of the workpiece, to analyze the changes in cutting force during processing. The simulated temperatures are 20°C, 200°C, 400°C, 500°C, 700°C, 800°C, 900°C, of which 500°C is the selected thermal cut-off point and the melting point is 938.25°C. The purpose of this article is to determine the relative magnitude of stress and temperature influence on processing as the temperature rises during processing.
2. Modeling and simulation experiment

2.1 Mathematical model
The simulation work piece is the fixed crystal direction of (111) crystal plane of single crystal germanium, the plastic properties of the material were used for simulation, and a material model was established to simulate the ductility conditions similar to metal processing. In order to reflect the plastic properties of hard and brittle materials under high pressure phase transition (HPPT), the model is selected as the pressure-sensitive Drucker-Prager constitutive model, which is used to adapt to pressure sensitivity and the resulting elastoplastic behavior. The model specifies the properties of the material, including elasticity, plastic behavior, heat transfer, thermal softening and strain rate sensitivity, the strain hardening behavior of the Drucker-Prager model is defined as:

\[
g\left(\varepsilon^p\right) = \sigma_0 f\left(T\right) \left(1 + \frac{\varepsilon^p}{\varepsilon_0^p}\right)^n
\]

Where \(\sigma_0\) is the initial yield stress, \(\varepsilon^p\) is the plastic strain, \(\varepsilon_0^p\) refers to the plastic strain, \(f\left(T\right)\) is the thermal softening function, and \(n\) is the strain hardening index. For brittle materials, in order to reflect the influence of high-pressure phase transformation, the initial tensile stress is taken as the value after the hardness value \(H/2.2\), and the initial compressive stress is taken as the hardness value \(H\). The hardness range of germanium is 9-11GPa, and this paper takes 10GPa. Since temperature is also an important factor affecting processing, the thermal softening function of the material is also extremely important for simulation. A fifth-order polynomial is established in the software to fit the thermal softening function, where \(c_0-c_5\) are polynomial coefficients, and \(T_c\) is the linear cut-off temperature, \(T_m\) is the melting temperature of the material.

\[
f\left(T\right) = c_0 + c_1 T + c_2 T^2 + c_3 T^3 + c_4 T^4 + c_5 T^5 \quad T < T_c
\]

\[
f\left(T\right) = f\left(T_c\right) \left(1 - \frac{T - T_c}{T_m - T_c}\right) \quad T \geq T_c
\]

Other workpiece parameters required for simulation are shown in Table 1.

| Material parameters | Elastic Modulus | Poisson's ratio | Hardness | Density | Thermal Conductivity | Specific heat capacity |
|---------------------|----------------|----------------|----------|---------|----------------------|-----------------------|
| Value               | 103GPa         | 0.278          | 10GPa    | 5350kg/m³ | 59.9W/m K         | 320J/kgK             |

2.2 Simulation scheme design
A two-dimensional orthogonal cutting finite element model is established in FEM software, as shown in Figure 1. The workpiece size is set to 0.08mm×0.02mm; the tool is natural single crystal diamond material; the tool parameters are set to: rake angle -45°, relief angle 5°, and the cutting edge blunt radius is 100nm. The simulation process selects turning micromachining simulation, does not use coolant, and sets the friction coefficient to 0.5.

Figure 1 Orthogonal cutting finite element model
In the FEM software two-dimensional simulation, it is possible to output cloud diagrams (see Figure 3), the cutting force and thrust force (see Figure 1). In the cutting process, the unit cutting force can indirectly represent the cutting energy. In order to study the influence of temperature on cutting force, by changing the temperature of the workpiece, the cutting force and cutting resistance at different temperatures are obtained, and the unit main cutting force and unit cutting resistance at different temperatures are obtained. The cutting process parameters are shown in Table 2.

Table 2 Process parameters

| Process parameters | Coefficient of friction | Cutting speed | Depth of cut | Cutting length |
|--------------------|-------------------------|---------------|--------------|----------------|
| Value              | 0.5                     | 60m/min       | 500nm        | 0.02mm         |

2.3 Simulation results and analysis

First, simulate the chip shape and temperature of single crystal germanium at room temperature. The simulation results are shown in Figure 2.

![Figure 2 Chip shape and temperature distribution at different times at room temperature](image)

It can be seen from Figure 2 that as the cutting progresses, the material accumulates to gradually form chips, and the temperature range gradually decreases. This is mainly due to the increase in the contact area between the tool and the material as the chips are formed, while the diamond tool has a good thermal conductivity.

Then by changing different temperatures, the simulation results are shown in Figure 3 (the results are all the cutting domain cloud diagrams in the last frame of the simulation). At the same time, the cutting force and unit cutting force values at different temperatures are obtained, as shown in Table 3. In the numerical simulation, all simulations The force results are based on the output under steady-state conditions.

![Figure 3 Simulation results at different temperatures](image)

| Temperature | Cutting domain cloud diagrams |
|-------------|-------------------------------|
| 20°C        | ![20°C](image)               |
| 200°C       | ![200°C](image)              |
| 400°C       | ![400°C](image)              |
| 500°C       | ![500°C](image)              |
| 700°C       | ![700°C](image)              |
| 800°C       | ![800°C](image)              |
It can be seen from Figure 3 that heating can reduce the hardness and brittleness of germanium, so the chip shape becomes thicker with the increase of temperature, and the heat-affected zone is mainly distributed on the back side of the chip ridge.

Table 3 Cutting force and unit cutting force at different temperatures

| Temperature (°C) | Cutting force (mN) | Thrust force (mN) | Unit cutting force (GPa) | Unit thrust force (GPa) |
|------------------|--------------------|------------------|-------------------------|------------------------|
| 20               | 210                | 390              | 21.0                    | 39.0                   |
| 200              | 207                | 390              | 20.7                    | 39.0                   |
| 400              | 191                | 386              | 19.1                    | 38.6                   |
| 500              | 180                | 380              | 18.0                    | 38.0                   |
| 700              | 143                | 288              | 14.3                    | 28.8                   |
| 800              | 90                 | 215              | 9.0                     | 21.5                   |
| 900              | 5                  | 6                | 0.5                     | 0.6                    |

It can be seen from Table 3 that when the temperature is less than 500°C, the cutting force and thrust force show a gentle downward trend with increasing temperature, but when the temperature is greater than 500°C and less than 700°C, the thrust force shows rapid decline and the cutting force decreases at a rate less than the thrust force. When the temperature exceeds 700°C, the cutting force and thrust force both show a rapid downward trend. When the temperature is close to the melting temperature (938°C), the workpiece (chip material) begins to accumulate on the rake face of the tool (complete chips are not formed). This phenomenon is due to the decrease in hardness and the increase in ductility at high temperatures. In the selected temperature range, the cutting force and the unit cutting force generally decrease as the temperature increases. In cutting, the sum of unit cutting force and unit thrust force can represent the total cutting energy in the cutting process. Therefore, the change trend of cutting energy with cutting temperature can be plotted (see Figure 4).

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Figure 3 Workpiece temperature distribution at different initial temperatures

Figure 4 The trend of cutting energy consumption with cutting temperature
subsequent cutting can achieve less Energy can cut the same material. The combined effect of temperature and stress is analyzed by the method of normalized cutting force. Firstly, a formula of normalized cutting force is established to solve the specific weight of stress and temperature on cutting under different temperatures. The formula is as follows:

\[ F = X \times S_f + Y \times T_f \] (4)

Among them, X, Y are scale factors, and X+Y=100%, S_f is the stress factor, and T_f is the temperature factor. The normalization process is to divide the simulated output cutting force at each temperature by the cutting force at normal temperature (20°C). Since the stress in the Drucker-Prager model has nothing to do with temperature, but only with pressure, S_f is taken as 1 in the normalization formula. The temperature factor is determined by dividing the hardness of the material at the corresponding temperature by the hardness of the material at room temperature. Then at 400°C, T_f is taken as 0.42, which is 4.2/10. Substituting the data into formula (12) can get:

\[ 98 = X(1) + Y(0.42) \]

Substituting Y=100-X, X=97%, Y=3%. This method can be used to calculate the proportion of stress and temperature to cutting force at other temperatures at the same time. See Table 4 for details.

**Table 4 The ratio of stress to temperature at different temperatures**

| Temperature (°C) | 20   | 200  | 400  | 500  | 700  | 800  | 900  |
|-----------------|------|------|------|------|------|------|------|
| Cutting force (mN) | 210  | 207  | 191  | 180  | 143  | 90   | 5    |
| Stress effect (%)  | 100  | 93   | 84   | 82   | 65   | 40   | 0    |
| Temperature effect (%) | 0    | 7    | 16   | 18   | 35   | 60   | 100  |

3. Conclusion

The ultrafine turning process of single crystal germanium was simulated by FEM software. By changing the single factor method, the temperature cloud map and cutting force of the workpiece and tool in the cutting region at different initial temperatures were obtained, and the curve was used to describe the cutting force. According to the sum of unit cutting force and unit thrust force to indirectly reflect the change of energy in the cutting process, it can be known that with the rise of temperature, the material can be softened, leading to a decline in the breaking strength, so the cutting energy decreases. Finally, through the normalized cutting force method, the comprehensive effect of temperature and stress in the cutting process is explored, as well as the specific weight of their influence on the cutting force, that is, with the increase of temperature, the influence of stress on the cutting force decreases gradually, while the influence of temperature becomes more and more obvious. The ultrafine turning process of single crystal germanium was simulated with finite element software. The influence on cutting force gradually decreases, while the influence of temperature becomes more and more obvious. This simulation is based on the global heating of the material, and subsequent research will consider realizing in-situ heating at the tool chip contact point.

Acknowledgments

This work was supported by the Jilin Province Science Development Fund Project (Approval Number: 20190302123GX, 20180414068GH).

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