Simulation Research on Vibration Cutting Mechanism of Metal Matrix Composites

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Abstract. Particle-reinforced metal composite materials have been widely used in the industry due to their excellent abrasion resistance and high strength, but they are typical hard-to-machine materials. A finite element model of the material matrix and enhanced particles have been established by the parametric modeling in this paper. Different from the previous development process, the particle is randomly distributed in this study, so the particle distribution has been better simulated than ever. The study shows that vibration-cutting particle-reinforced composites have reduced the phenomenon of particle suspension on the machined surface compared to conventional cutting, and the high-elastic-modulus reinforcing particles have been subjected to high stress, and the matrix between the particles have acted as a stress-transmitting “channel”. When the particle’s diameter is 20μm and the volume fraction is 30%, there is a stress transmitting channel in a certain range away from the tool tip. When the cutter contacts the particles, the vibration cutting will cause the initial crack near the particle, which cut off part of the stress transmitting channels, make the stress concentrated on the tool tip and lead to the material easier to remove.

Keywords: ABAQUS; parameter modeling; particle reinforced composites; vibration cutting.

1. Introduction
In many fields, traditional homogeneous metal materials have been unable to meet the diverse needs of human pursuit, such as light weight and high strength. Researchers have combined materials to create a wide variety of composite materials based on the desired properties. Among them, Metal Matrix Composites (MMCs) have the advantages of high strength, high modulus, high temperature resistance, non-flammability, etc., and they are widely used in military, aerospace, electronics and other industries requiring lightweight and high strength. The particle reinforced metal matrix composites have the characteristics of both the reinforced particles and the metal matrix. They have not only small mass and thermal expansion coefficient, but also high specific strength and stiffness. The removal form of the particle reinforced composite material can be divided into four types: 1) the matrix and its inclusions together form chips; 2) the particles are pressed into the matrix material; 3) the particles are debonded due to crack propagation; 4) particles are crushed by extrusion. In the four modes, there are pits on the machined surface by debonding of the particle. The broken particles plough machined surface with the cutter, and leave grooved scratches of different depths. Therefore, the quality of machined surface of composite material is much lower than that of pure metal material due to the existence of reinforced particles, and there are a lot of defects (particle debonding, fracture, ploughing surface, etc.). Ultrasonic vibration cutting is based on traditional cutting, which is applied to the tool or workpiece to achieve pulsed cutting. More and more studies have shown that this cutting method can reduce the cutting force, improve the stability of the machining process, and inhibit the occurrence...
of machining damage \cite{7}. Lu Shihong \cite{8} used ABAQUS to study the formation mode of titanium alloy Ti-6Al-4V and H13 hardened steel under high strain rate and the formation mechanism of sawtooth chip under orthogonal cutting conditions. But it takes a long time to build a cutting simulation model. Jing xiu bing\cite{9} modified J-C constitutive relation and Cockroft-Latham cutting fracture criterion. A three-dimensional ultra-precision cutting finite element model was established based on the large deformation Lagrange finite element theory. In order to study the effect of cutting conditions on the surface quality of ultra-precision cutting, a large number of mouse operations are needed in the finite element simulation process, which is particularly cumbersome.

In this study, parametric modeling is realized by means of script program, and the inefficient modeling work is avoided. The particle distribution algorithm is characterized by variable volume fraction, variable size, random radius, random particle distribution and no crossover. It lays a technical foundation for the further study of the influence of the size, the number and the distribution of the enhanced particles on the processing. By changing the amplitude curve used in velocity boundary conditions, the traditional cutting and vibration cutting are compared and analyzed by using the same model. The effects of vibration on cutting force, particle removal time and matrix damage and fracture are studied. The influence of the addition of reinforcing particles on the cutting force, surface quality, stress distribution and propagation of the metal matrix material, and the initiation and crack propagation of the metal matrix material will be studied.

2. Script-based Parameterized Finite Element Modeling of Particle Reinforced Composites

In the finite element modeling of reinforced particles, the material model of reinforced particles is set as an isotropic linear elastic model. The matrix material is the same as the pure metal material, which is simulated by the elastic-plastic model. Material parameters of matrix, reinforced particles and cutting tools are shown in Table 1. There are two simulation methods of particle distribution, one is periodic distribution, and the other is random distribution. The random distribution model of particles can fully consider the interaction between particles to a certain extent. The model can reflect the microstructure distribution of particle reinforced composites and accurately simulate the elastic modulus of composites \cite{10}. In this study, the volume fraction of particle reinforced metal matrix composites is low volume fraction. Particle size is 20 microns.

### Table 1. Material properties of metal matrix and particle and tool \cite{11,12}.

| Material          | Density (kg·m⁻³) | Elastic Modulus (GPa) | Poisson's ratio | Thermal Conductivity (W·m⁻¹·K⁻¹) | Specific heat capacity J (Kg·°C)⁻¹ |
|-------------------|------------------|-----------------------|----------------|----------------------------------|----------------------------------|
| AL6061            | 2700             | 68.9                  | 0.33           | 167                              | 896                              |
| SiC               | 3100             | 408                   | 0.183          | 490                              | 670                              |
| Cemented carbide tool | 4250             | 850                   | 0.08           | 2100                             | 525                              |

2.1. Material Constitutive Model and fracture Criterion

An elastoplastic constitutive equation is used to simulate the matrix material from the initial state until the damage in the metal matrix material model. The J-C viscous material model is used to simulate the properties of the matrix material. This model is often used to simulate the constitutive model of materials with large strain, high strain rate and high temperature. The following formula represents the basic form of the J-C model of von-Mises stress \( \sigma \) \cite{13}:

\[
\sigma = (A + Br^\alpha) \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left( 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^n \right)
\]

\( A, B, C, \alpha, n, \dot{\varepsilon}_0, T_m, T_r \) are parameters that need to be determined. The following formula is used for the conduction heat transfer:

\[
\dot{Q} = \frac{A_{ij} \kappa_{ij} \nabla^2 \theta}{\kappa_{ij} \kappa_{ji}}
\]

where \( A_{ij} \) is the thermal conductivity matrix of the material, \( \kappa_{ij} \) is the thermal conductivity of different directions, and \( \nabla^2 \theta \) is the temperature gradient.
Equation (1) consists of three parts. The effects of strain hardening $f_1(\varepsilon)$, strain rate strengthening $f_2(\dot{\varepsilon})$ and thermal softening $f_3(T)$ on flow stress are considered respectively. In the equation, $\varepsilon$ is the equivalent plastic strain, $\dot{\varepsilon}$ is the plastic strain rate, and $\dot{\varepsilon}_0$ is the reference strain rate. $T$ and $T_m$ respectively represent the current temperature and the material melting temperature, and the $T_r$ indicates the conversion temperature. When the temperature is below $T_r$, the material properties will no longer change with temperature. Five material constants $A$, $B$, $C$, $n$, and $m$ were measured by torsion tests, static tensile tests, and Hopkinson bar dynamic tensile tests on different materials. The parameters of the J-C constitutive model are shown in Table 2. The parameters of the constitutive model of aluminum matrix can be obtained by correlative calculation.

| Material | A (MPa) | B (MPa) | C   | n   | m   | $T_m$ (°C) | $T_r$ (°C) |
|---------|---------|---------|-----|-----|-----|------------|------------|
| AL6061  | 324     | 114     | 0.002 | 0.42 | 1.34 | 582        | 20         |

2.2. The Establishment of Finite Element Model

Based on the commercial finite element software ABAQUS/explicit, a two-dimensional orthogonal cutting model for ultrasonic vibration cutting is established which is composed of two parts: workpiece and tool, and a micromechanical model including matrix phase and particle phase are established. The tool is set as an analytic rigid body. The cutter boundary condition assumes that the direction of speed is horizontal, and the speed is the actual linear speed of turning. The periodic amplitude curve in the finite element software ABAQUS is used to exert uniform velocity load on the tool. The amplitude curve is set for the corresponding vibration period and the vibration direction and cutting direction are in the same straight line to realize the effect of vibration cutting. Figure 1 shows the particles contacted by the tool in turn, numbered in order of contact with the tool.

![Figure 1. Two dimensional orthogonal cutting geometry model for particle reinforced composites](image)

In the modeling process of particles reinforced composites, the geometric model is related to the random distribution of particles in metal matrix. In the two-dimensional plane, the geometric model is a solid rectangle with a certain size. In the solid rectangle, there are a certain number of solid circles. In actual conditions, the distribution of particles is basically irregular. The real particle size in composite materials is often a certain range and the radius can be changed. It also helps to study the change of particle size on the effect of processing of the same cutting parameters. The algorithm is used to realize the variable number of particles, so it is convenient to study the effect on the machining effect of the same cutting parameter when the particle volume fraction is increased or decreased. In the two-dimensional graph, there is no overlap between the particle and the workpiece boundary, and between two particles. In order to obtain a better mesh shape in the later generation of meshes, there is a certain distance between the geometric boundaries. Overall, there are the following principles: 1) the center of the circle is random; 2) the radius can be changed; 3) the quantity can be changed; 4) there is no intersection between the geometric boundaries.
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3.1. Cutting Simulation Design
When both the particles and the matrix in the geometric model have the same properties of the metal Al6061 material, the workpiece becomes homogeneous metal Al6061 material. It can also be regarded as the aluminum reinforced aluminum matrix composite. The particle and matrix parts of the geometric model generated by the script are respectively assigned to the corresponding SiC and Al6061 material properties. The workpiece model simulates the SiC particle reinforced aluminum matrix composite material. Simulation parameters are shown in Table 3.

Table 3. Simulation vibration parameters.

| Parameter | Tool parameter | Vibration parameter | Cutting parameter |
|-----------|----------------|---------------------|-------------------|
|           | Rake angle | Relief angle | Amplitude | Frequency | Cutting speed | Back cutting depth |
| Numerical | 10°       | 10°           | 20μm       | 25kHz     | 1.57 m·s⁻¹   | 30μm              |

3.2. Study on Meso-characteristics of Surfaces of Particle Reinforced Aluminum Matrix Composites
The graphs a) and b) in figure 2 respectively reflect the machined surface of the aluminum-based material during conventional cutting and vibration cutting, and it can be seen that both are relatively flat. It is worth noting that the conventionally machined surface of aluminum-based materials has a thin stress layer, but is not uniform; and the machined surface after vibration cutting is thicker and more uniform than conventional cutting. The simulation results show that vibration cutting has the characteristics of improving the thickness and uniform distribution of the stress surface layer in the substrate metal compared with conventional cutting.

Figure 2. Machined surfaces of aluminum matrix material

The graphs a) and b) in figure 3 show the machined surfaces of particle reinforced aluminum matrix composites in conventional cutting and vibration cutting respectively. Due to the addition of reinforcing particles, the machined surfaces of both are uneven (the pits left by the removed particles and the bulge of the particles that have not been removed.), and there are cases where the particles are suspended and the particles below the cutting path are incompletely de-bonded. The graph a) in figure 3 shows that there is a large area of stress concentration around the incompletely particles debonding below the cutting path in traditional cutting except for the obvious suspension of particles. The graph b) in figure 3 shows that the phenomenon of particle suspension on the machined surface of vibration cutting is reduced, and the area of stress concentration around incomplete debonding particles is smaller. The incomplete debonding particles and the stress concentration area under the cutting surface will affect the production and propagation of the cracks in the workpiece. The simulation results show that the vibration cutting can improve the uniform distribution of the stress on the machined surface and reduce the residual material on the machined surface compared with the common cutting for the particle reinforced metal matrix composites.
3.3. Study on Meso-fracturing Mechanism of Cutting Zone in Granular Reinforced Aluminum Matrix Composites

It is found that the stress distribution has been changed because of the addition of reinforced particles in the metal matrix during cutting. In the cutting process of particulate reinforced metal matrix composites, "particle pairs" are easily formed between adjacent particles when the tool contacts to the reinforced particles. In addition to the large stress of the particles, the stress between the pair of particles is also large, which acts as a "channel" for stress transmission, and the stress is transferred to the adjacent particles. The graphs a) and b) in figure 4 respectively show the stress distribution and transmission of the tool contact to the No. 2 particle in conventional cutting and vibration cutting. It can be clearly seen from the figure that both traditional cutting and vibration cutting have stress transfer "channels", but the "channels" are more obvious in traditional cutting conditions. In the cutting process, due to the ultrasonic vibration applied by the tool, the stress transferring is blocked and the "channel" is cut off, which results in the stress concentration in the smaller cutting deformation zone. The matrix is more easily to failure and fracture under this stress concentration condition, and macroscopically, the material can be removed by only a small cutting force, which is beneficial to cutting.

3.4. Study on the Cutting Force of Microscopic Model of Particle Reinforced Aluminum Matrix Composites

Figure 5 shows the tool is in contact with particle No. 5 (t=56μs) to complete particle debonding (t=58μs) during vibration cutting. At the time of 56 μs, the tool begins to contact the particle, the cutting macroscopic force reaches the maximum value, and the initial crack appears near the particle. At the time of 57 μs, the tool and the particle continue to contact, the cutting macroscopic force begins to decrease, and the stress is transmitted along the direction of crack propagation. At the time of 58 μs, the tool is still in contact with the particles, and the stress value and the macroscopic force decrease to the lowest value, which indicates that the stress has been completely released, the material has been removed and the chip is produced.
4. Conclusions
In this paper, the microscale characteristics of stress distribution and transfer on the machined surface of particle reinforced composites under vibration cutting and the micro-model cutting force are studied. The findings are as follows:
1) The particle’s suspension on the machined surface of vibration cutting is reduced, and the stress concentration zone around incomplete debonding particles is smaller, the surface stress distributes uniformly and is relatively smooth;
2) When the particles reinforced composite is machined, it is easy to form "particle pair" between adjacent particles. Vibration cutting can cut off "channel", which is beneficial to cutting;
3) Under the condition that the tool contacts the same particle, the cutting force of vibration cutting is less than that of traditional cutting, which is beneficial to material removal;
4) The simulation model in this study adopts the script parametric modeling, which shortens the modeling time and improves the modeling efficiency. The random distribution of particles is helpful to
better simulate the real micro-morphology of composite materials. Ultrasound vibration cutting can cut off the "channel" of stress transfer between "particle pairs". The parameters of ultrasonic vibration machining were optimized by changing the volume fraction and particle size. It is very important for particle reinforced metal matrix composites to be used in practical machining.

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