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Simulation Study of Micro Interface Damage of Particle Reinforced Metal Matrix Composites on Vibration Cutting

Liang Yang[1]*, Chunguang Xu[1], Zhengjiang Wang[2]

[1.]Dalian Jiaotong University. College of Mechanical Engineering.Dalian.China

[2.]University of Strathclyde. CPM.DMEM. Glasgow, UK

* corresponding author: yangliang@djtu.edu.cn

Abstract. The finite element simulation of the micro interface of SiCp/Al composites under ultrasonic vibration cutting is described. The constitutive relationship of the matrix, SiC particles and interface is analyzed respectively, and a "matrix-interface-particle" dynamic physical simulation model is given. The cutting conditions of a single particle in three different cutting paths are simulated, and the removal mechanism and interface damage characteristics of SiC particles is analyzed. The reliability of the simulation results is analyzed by observing the SEM photos of the experimental samples.

1. Introduction

Particle-reinforced metal matrix composites have good mechanical and thermal properties and are promising engineering material, but their poor processability has prevented their wider application. Ultrasonic-assisted cutting is a hybrid machining technique in which cutting tools vibrate at high frequencies and low amplitudes. This is a technology suitable for difficult-to-machine materials.

As early as 2004, Wu Yan studied the surface residual stress of SiCp/Al composites under ultrasonic vibration. Results showed that compressive stress can improve the fatigue strength of materials[1]. A. Pramanik established a mechanical model capable of predicting the stress of ceramic particles reinforced aluminum alloy during micromachining [2]. Uday A. Dabade believed that the tool-chip interface friction problem in the processing of silicon carbide particle reinforced metal matrix composites is caused by the two-body wear and three-body rolling owing to the presence of the reinforcement in the composite [3]. Xiaoliang Jin proposed a slip line length model considering the change of stress in the material deformation zone under the influence of the cutting edge radius [4]. S. Sikder proposed an analytical force model to predict the cutting force during the processing of metal matrix composites and studied the effect of the particle size on the cutting force[5]. A. Ghandehariun proposed a constitutive model suitable for microscopic particle cutting simulation. This model correlated particle size and particle volume fraction of metal matrix composites and studied the different mechanisms of material failure in the main shear zone during the cutting process [6,7]. L. Z. Sun established a mechanical behavior model of particle reinforced metal matrix composites with particle cracks. An elastoplastic constitutive model based on mesomechanics, combined with particle crack damage mechanics, was used to predict the overall mechanical behavior of particle reinforced metal matrix composites [8]. Wei Bai studied the use of carbide and diamond tools to compare the cutting performance and tool wear of silicon carbide particle reinforced aluminum-based composites under dry ultrasonic-assisted turning and conventional turning conditions [9].

In summary, most of the researches focus on the research of cutting force or surface damage, such as matrix damage and particle breakage and debonding. The research on the interface damage between the matrix and particles and the interface crack propagation is rarely reported. Based on the previous cutting simulation technology, in this paper, a two-dimensional simulation model of the matrix in which particles and interfaces are at the micro-scale is established. The aim is to explore the internal structural changes such as substrate damage, particle breakage and interface debonding during vibration cutting.

2. Establishment of the constitutive model

2.1. Model of Al matrix constitutive.

The Al matrix is regarded as a thermo-elastoplastic material. Assuming that the flow stress of the Al matrix is independently affected by strain, strain rate, and temperature during the cutting process, the Johnson-Cook (J-C) constitutive model is used to describe its plastic behavior, and its constitutive equation is as follows [10]:

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

In formula (1), ε is the equivalent plastic strain, $\dot{\varepsilon}$ is the equivalent plastic strain rate, $\dot{\varepsilon}_0$ is the reference equivalent plastic strain rate, and T is the operating temperature. The constitutive equation of J-C has five material constants, A is the yield stress constant, B is the strain hardening constant, n is the strain hardening index, C is the strain rate hardening constant, and m is the temperature-dependent coefficient. T_r and T_m respectively represent room temperature and material melting temperature.

According to the J-C damage criterion, the expression of unit damage is as follows:

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon_f} \tag{2}$$

In formula (2), $\Delta\varepsilon$ is the increase of the equivalent plastic strain in the integration step, and ε_f is the equivalent plastic strain when the Al matrix starts to fail. D is the parameter of unit damage. When D = 1, unit damage will occur and then removed from the calculation. The fracture strain can be calculated according to the following expression[11]:

$$\varepsilon_f = \left[D_1 + D_2 \exp\left(D_3\sigma^*\right)\right]\left[1 + D_4 \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 + D_5\left(\frac{T - T_r}{T_m - T_r}\right)\right] \tag{3}$$

Where, D_1 ... D_5 are material constants.

2.2. Establishment of the constitutive model of SiC particles

Compared with the Al matrix, SiC particles have higher rigidity and stiffness and follow the generalized HooK's law before fracture, which is a completely linear material. After elastic deformation of SiC particles, almost no plastic deformation occurs, but cracks occur directly. The brittle fracture damage model simulates the brittle fracture of SiC particles. The initiation crack of the particles is detected following the normal stress criterion. The normal stress criterion is given by equation (4) [12]:

$$\max\left(\sigma_1, \sigma_2, \sigma_3\right) = \sigma_0 \tag{4}$$

In the formula(4), σ_0 is the tensile strength of the SiC particle.

2.3. Inter facial cohesion model

In the simulation of particle-reinforced metal composite vibration cutting, the cohesive force unit is used to model the interface layer. As shown in Figure.1, the cohesive force unit transfers stress and displacement between the particles and the matrix through a common node. In this method, the matrix, particles, and interface are always in one component, which avoids the definition of assembles, contacts and constraints, but it has complex meshing.

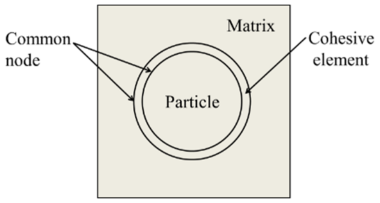


Figure 1 Interface layer modeling method

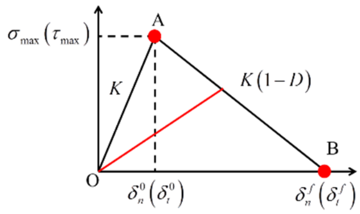


Figure 2 Traction separation criteria

The interface failure process is divided into two processes: 1) The linear elastic phase is the OA segment as in Figure 2. The interface stress starts to increase with the increase of displacement under the effect of external load. When the stress at the interface reaches the maximum, material damage starts and initial cracks sprout; 2) The linear softening stage is the AB segment. As the displacement increases, the stress at the interface decreases. At this time, the interface's ability to withstand external loads decreases. The cracks produce and expand inward; when the stress drops to zero, the cracks at the interface completely expand and the particle fractures. As shown in Figure 2, the damage variable D represents the overall damage of the material and the combined effects of various movement mechanisms. When D = 0, the damage of the cohesive unit did not begin; when D = 1, the complete damage of the cohesive unit failed.

$$\sigma_n = \begin{cases} (1-D)\overline{\sigma_n} & \overline{\sigma_n} \geq 0 \\ \overline{\sigma_n} & \text{other} \end{cases} \tag{5}$$

$$\tau_s = (1\text{-}D)\overline{\tau_s} \tag{6}$$

$$\tau_t = (1\text{-}D)\overline{\tau_t} \tag{7}$$

In the formula(5), (6), (7), $\overline{\sigma_n}$ 、 $\overline{\tau_s}$ 、 $\overline{\tau_t}$ represent stress components corresponding to no damage.

2.4. Construction of SiCp/Al composite model

The diameter of reinforced particles is generally from several microns to tens of microns, and the interface thickness is even smaller, so in this paper, a finite element model in a micro-scale is established. A dynamic physical simulation model of "matrix-interface-particle" under vibration cutting conditions was established using the cohesion model and parting lines. The distribution of particles is uniform, the average particle diameter is 20μm, the interface thickness is the same and uniform, and the interface thickness is 1μm.

3. Simulation of particles in different cutting paths

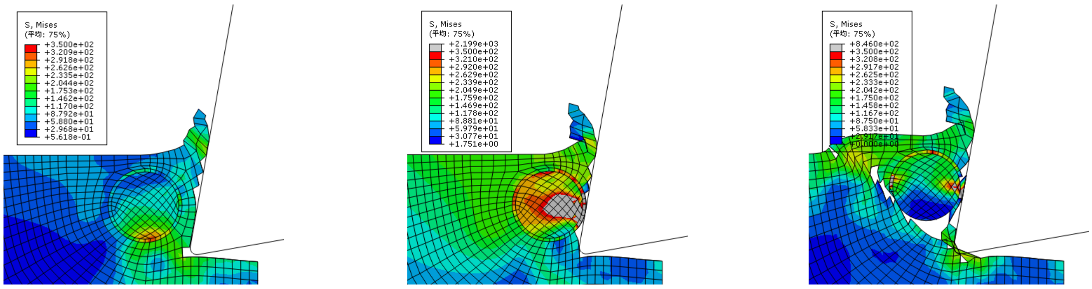
By establishing a simulation model of three different cutting positions of a single particle relative to the cutting path, that is, the particle is above the cutting path, the particle is in the middle of the cutting path, and the particle is below the cutting path. Stress-strain distribution and damage status for matrix, interface, and particles are analyzed during one-dimensional ultrasonic vibration cutting. The simulation cutting parameters are shown in Table 1

Table 1. Simulation cutting parameters.

Parameter	Tool parameter		Vibration parameter		Cutting parameter	
	Rake angle	Relief angle	Amplitude	Frequency	Cutting speed	cutting depth
Numerical	10°	10°	5μm	20kHz	$0.39 m\cdot s^{-1}$	30μm

3.1. Particles are above the cutting path

The vibration cutting simulation process of particles above the cutting path is shown in Figure 3. When the tool starts to cut the matrix, stress concentration occurs in the part of the particle and interface close to the tooltip. The interface layer transmits stress to the particle at t=34μs, the tool starts to separate from the workpiece Figure 3a). At t= 58μs, when the second cycle of cutting is performed, the force of the particles and the interface layer are increased. The stress concentration phenomenon reappeared, and the stress value reached the maximum value (Figure 3b. 2199MPa), at the same time, the area of stress was increased. However, the stress on the particles did not reach the stress limit of the brittle fracture of the particles, the brittle fracture of the particles did not occur. The interface layer under the particles failed, as shown in Figure 3c. At t= 66μs, as the tool continues moving forward, due to the plasticity of the matrix, the particles slip upward along the shear plane under the action of the rake face, and the interface layer and the matrix both failed.

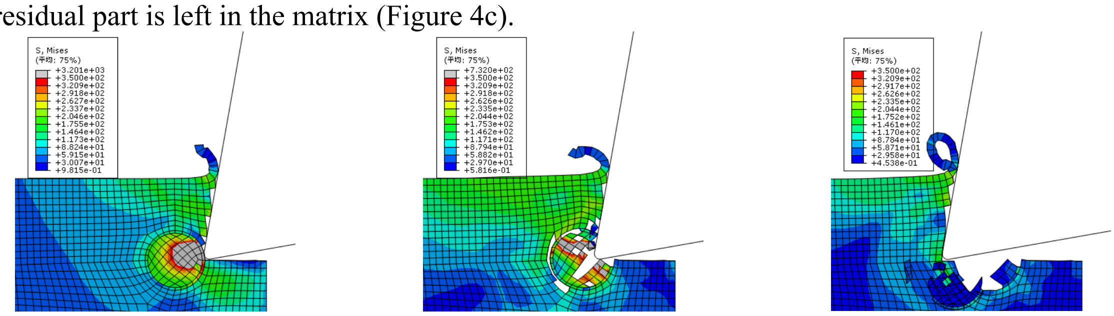


a) t=34μs b) t=58μs c) t=66μs

Figure 3 Simulation process of vibration cutting of particles above the cutting path

3.2. Particles are in the middle of the cutting path

The simulation process of the vibration cutting of particles in the middle of the cutting path is shown in Figure 4. When the tool is cut into the workpiece, the stress concentration phenomenon occurs in the particles and the interface. This phenomenon is mainly manifested in the interface layer, and the stress of the interface layer is greater than that of the adjacent particles and the matrix. At t= 56μs, the particle and interface stress increases but no failure occurs (Figure 4a); when the stress on the particle reaches the fracture limit of the brittle particle, the interface fails, the particle begins to fracture, and the crack starts to expand from the tip position into the internal of particles (Figure 4b); Then, the particles are cut open along the direction of the crack, the chips are separated from the workpiece and the residual part is left in the matrix (Figure 4c).



a) t=56μs b) t=63μs c) t=115μs

Figure 4 Simulation process of particle vibration cutting in the middle of the cutting path

3.3. Particles are below the cutting path

The simulation process of the vibration cutting of the particles under the cutting path is shown in Figure 5 because the particles are under the cutting path, the tool cuts the matrix, the top of the particles is extruded by the matrix, and the stress concentration appears in the interface. At t=68μs, tooltip contacts the interface, the interface layer fails. Then, the rear face of the tool contacts the particles, and the particles are acted by the plowing force of the flank (Figure 5a. 3796MPa). A small

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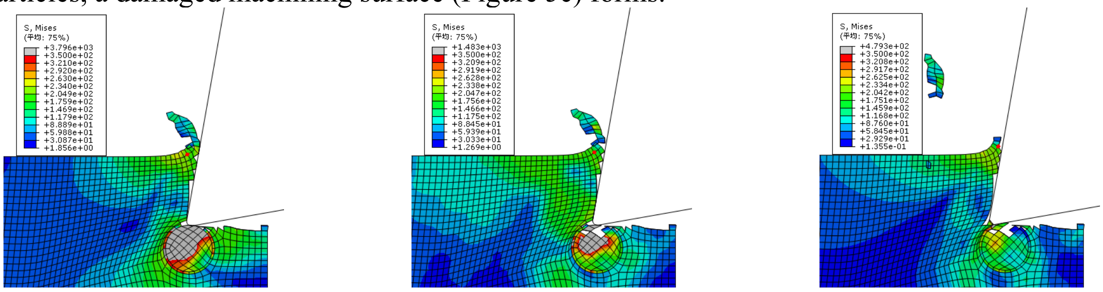
part of the particles appears minor damage at t= 69μs (Figure 5b); When t= 80μs, the tool cut through the particles, a damaged machining surface (Figure 5c) forms.



a) t=68μs b) t=69μs c) t=80μs

Figure 5 Simulation process of particle vibration cutting under the cutting path

4. Analysis of cutting experiment results

To verify the above simulation results, the ultrasonic vibration cutting system is established as shown in Figure 6. Among them, the machine is CK0640D CNC lathe, the spindle speed range is 100-4000r/min, and the control accuracy is 0.1μm. The material of the workpiece to be cut is a SiCp/Al composite test piece with a diameter of φ25 × 4mm. The ultrasonic generator is produced by Koki (Shanghai) Electronic Technology Co. Ltd, and its frequency is 20kHz. The cutting tool used in the cutting process is a cluster diamond tool (PCD), the tool model is DCGT11T302, the rake angle and rear angle of the tool is 7°, and the cutting edge radius is 0.2mm.

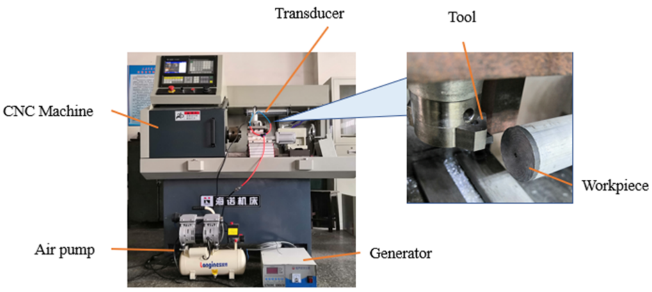
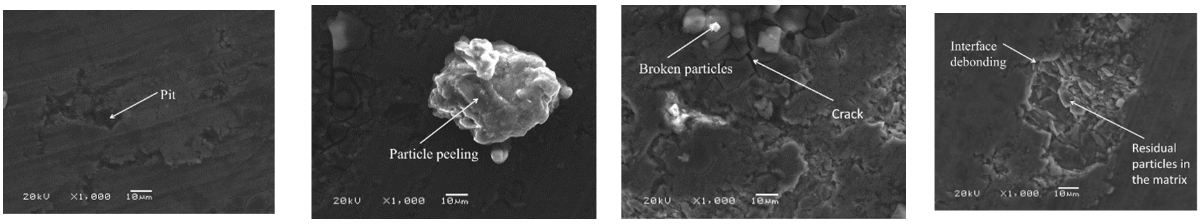


Figure 6 Experimental device of ultrasonic vibration cutting

A scanning electron microscope (SEM) test was performed on the processed surface of the SiCp/Al composite, as shown in Figure 7. Irregular voids were found on the surface of the SiCp/Al composite after ultrasonic vibration cutting, as shown in Figure 7a. This is caused by particles peeling from the matrix during cutting. At the same time, as shown in Figure 7b, relatively intact particles were also found on the surface of the SiCp/Al composite, which precisely illustrates the existence of the above-mentioned detachment phenomenon. This phenomenon is consistent with the simulation results of the particles above the cutting path in Figure 3. After the particles are separated from the matrix as a whole, a cavity is left in the matrix. From Figure 7c, it can be seen that the particles break during the cutting process, and a part formed chips to separate, and the other part remained in the matrix. At this time, there is no crack in the particle. From Figure 7d, interface debonding was found at the edges of the particles. It is clear that the particles first debonded and then cut off. This phenomenon is similar to the simulation results of the particles in the middle of the cutting path in Figure 4.



a) b) c) d)

Figure 7 SEM test pictures of SiCp/Al composites

It can be seen in Figure 7c that the particles have broken and cracks have spread to the surrounding area, which indicates that a strong interaction occurs between the tool and the particles. This phenomenon is consistent with the simulation results of the particles under the cutting path in Figure 5.

5. Conclusion

This paper describes the micro-finite element simulation of ultrasonic vibration cutting of SiCp/Al composites and establishes the dynamic physical simulation model of "matrix-interfacial particle" of SiCp/Al composites under vibration cutting conditions. The single-particle was simulated in three different cutting paths, and the removal mode of SiC particles was analyzed. Above the cutting path, the interfacial debonding causes the particles to be separated from the matrix. In the middle of the cutting path, brittle fracture occurs and cracks form. Some of the particles are separated from the matrix, while the rest will remain in the matrix. Below the cutting path, the particles are partially broken to form cracks and pressed into the matrix. By observing SEM photos of experimental samples, the results are consistent with the simulation results.

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