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# Micro Finite Element Simulation of Cutting Process of SiCp/Al Particle Reinforced Composites

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# Micro Finite Element Simulation of Cutting Process of $SiC_p$/Al Particle Reinforced Composites

## Simulation of Cutting Process

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***Abstract*—In order to reveal the cutting mechanism of SiCp/Al particle reinforced composites, the micro structure model of random distribution of particles was established based on Python script language by using ABAQUS, the prediction of machined surface morphology and chip morphology was realized. The validity of the model is verified by comparing with the experimental results.**

***Keywords*— $SiC_p$/Al composites; cutting simulation; surface morphology; chip morphology**

## I. INTRODUCTION

$SiC_p$/Al particle reinforced composite has high specific modulus, high specific strength, low coefficient of thermal expansion, excellent fatigue and corrosion resistance.It is a very promising material. It has been widely used in aerospace, automotive, electronic and military fields. However, due to the existence of reinforced particles, the tool wear is serious in the cutting process, the surface quality is poor, which seriously hinders its wide application. Therefore, the cutting mechanism of $SiC_p$/Al particle reinforced composites has attracted extensive attention of scholars. Finite element simulation is one of the main means to study the cutting mechanism. Using the finite element software LS-DYNA, Wang Yangjun [1] established a two-phase mixed numerical simulation model of $SiC_p$/Al composites with a volume content of 45%, which revealed the formation mechanism of processing surface defects. Fathipour et al. [2] used ABAQUS to study the cutting process of $SiC_p$/Al composites with volume content of 20%, compared the chip morphology with the experiment to verify the validity of the model. Liu [3] established a single particle $SiC_p$/Al Composites simulation model with a volume fraction of 45%, studied the surface defects of the micro model by simulation of different cutting depths. Umer [4] uses Johnson cook fracture criterion based on equivalent strain, strain rate and temperature, adopted two kinds of $SiC_p$/Al composites cutting models of preset separation line and no separation line, respectively. Huang Shutao [5] established a simulation model according to the shape and distribution of particles in the metallographic picture of $SiC_p$/Al composites. The cutting force, boundary damage and defects of $SiC_p$/Al composite in high-speed turning were simulated. Fu Cheng [6] established the cutting model of $SiC_p$/Al composites, the particles were regarded as linear elastomer materials, the distribution of temperature and strain in the cutting process was obtained. Wang [7] established the finite element model of $SiC_p$/Al composites with uniform distribution by using ABAQUS, analyzed the influence of different cutting speed and depth on cutting force and stress field distribution. Sun[8] applied the explicit solver in ABAQUS, based on the Johnson cook constitutive equation at the micro scale, simulated the micro drilling process of $SiC_p$/Al composites with three-dimensional finite element model. Xu [9] based on ABAQUS, established a three-dimensional homogeneous model of $SiC_p$/Al composites milling, and studied the distribution of residual stress on the machined surface. [10] Hu established a three-dimensional homogeneous model to simulate the effect of a 3-micron diameter pecker on the drilling of $SiC_p$/Al composites. In the existing simulation research, in order to simplify the modeling, it is usually assumed that the particles are uniformly distributed, which is not consistent with the actual situation. Therefore, in order to further reveal the cutting mechanism of $SiC_p$/Al particle reinforced composite materials, this paper uses the random distribution micro structure model of $SiC_p$/Al particles based on Python script language to realize the prediction of machined surface morphology and chip morphology, and verifies the validity of the model through experiments.

## II. ESTABLISHMENT OF FINITE ELEMENT MODEL

### A. *Selection of constitutive model.*

Metal cutting process is a thermo-mechanical coupling process, The effects of strain, strain rate and temperature must be considered simultaneously. The Johnson cook constitutive model comprehensively considers the influence of thermal softening, strain and strain rate strengthening on the material stress. Therefore, in this paper, the Johnson cook constitutive model is used to characterize the dynamic mechanical properties of 2024Al. Its expression is as follows:

$$\bar{\sigma}=\left[A+B\left(\bar{\varepsilon}^{pl}\right)^{n}\right]\left[1+C\ln\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0}\right]\left[1-\frac{\theta-\theta_{tran}}{\theta_{melt}-\theta_{tran}}\right]^{m} \quad (1)$$

Where: A is the yield strength under quasi-static condition;is material defect density characteristic parameter; B, n is the

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strain hardening parameter; C is the strain rate strengthening parameter; 25 is usually used at room temperature, $\theta_{tran}$ is taken as the material melting point; m is the thermal softening parameter. The Johnson cook constitutive parameters of 2024Al are given in TABLE I.

TABLE I. JOHNSON-COOK PARAMETER OF 2024AL ALLOY [12]

| Material | A/MPa | B/MPa | C | m | n |
|---|---|---|---|---|---|
| Al2024 | 218 | 546 | 0.038 | 3.73 | 0.335 |

Johnson cook fracture criterion can well reflect the chip separation status of metal materials under different cutting conditions [11], and can get more reasonable cutting results, such as cutting force, cutting temperature, residual stress, chip morphology, etc., so the John cook damage model used in this paper is expressed as:

$$\bar{\varepsilon}_0^{pl} = [d_1 + d_2 \exp(d_3 \frac{p}{q})][1 + d_4 \ln(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0})][1 + d_5(\frac{T - T_{room}}{T_{melt} - T_{room}})] \quad (2)$$

Where, $d_1$~$d_5$ is the material failure model coefficient, $p$ is the average principal stress, $q$ is the flow stress. $\bar{\varepsilon}_0^{pl}$ is the equivalent strain at the time of material failure. The Johnson cook damage parameters for 2024Al are given in TABLE II:

TABLE II. JOHNSON-COOK FAILURE PARAMETERS OF 2024AL MATRIXTABLE STYLES [13]

| $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ |
|---|---|---|---|---|
| 0.13 | 0.13 | -1.5 | 0.011 | 0 |

Cutting process of $SiC_p$/Al composite materials, brittle and hard particles are prone to brittle fracture and failure. In order to truly reflect the damage evolution process of particles, in the simulation model, the brittle fracture model of SiC particles is introduced, which has been used in the simulation cutting of reinforced particle composite materials for many times [3,5].

The fracture energy criterion is used to control the failure evolution behavior of SiC particles. The crack start displacement can be calculated by the following formula:

$$u_{n0} = 2G_f^I / \sigma_{tu}^I \quad (3)$$

Where, $G_f^I$ is the mode fracture energy of the material, $\sigma_{tu}^I$ is the failure stress when the mode crack is formed.

The effect of shear stress on the failure evolution of SiC particles is described by using the functional shear stress retention model. The shear modulus of SiC granular materials at failure evolution stage can be calculated by the following formula:

$$G_S = \rho\left(\varepsilon_{nn}^{ck}\right) G \quad (4)$$

Where, $G$ is the shear modulus before material failure, $\rho\left(\varepsilon_{nn}^{ck}\right)$ is the shear retention factor of the material, and its calculation formula is as follows:

$$\rho\left(\varepsilon_{nn}^{ck}\right) = \left(1 - \frac{\varepsilon_{nn}^{ck}}{\varepsilon_{max}^{ck}}\right) \quad (5)$$

Where, $\varepsilon_{nn}^{ck}$ is the cracking strain of SiC particles, $P$ and $\varepsilon_{max}^{ck}$ are material parameters. Main model parameters are given in TABLE III:

TABLE III. MAIN MODEL PARAMETERS OF SIC BRITTLE FRACTURE [13]

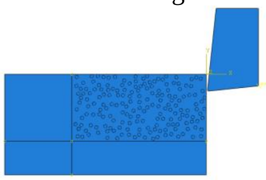
| $\sigma_b\left(MPa\right)$ | $G_f^I\left(J/m^2\right)$ | $P$ | $\varepsilon_{max}^{ck}$ |
|---|---|---|---|
| 1500 | 30 | 1 | 0.001 |

*B. Micro modeling of $SiC_p$/Al Composites*

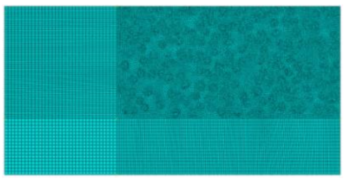
The micro structure model of $SiC_p$/Al multi-particle random distribution is established by using the script language Python on the finite element software ABAQUS. The volume fraction of particles is approximately calculated by the area ratio, accounting for about 20%. The matrix size is 0.6 × 0.3; the particles are randomly distributed in the 0.4 × 0.2 region.

The basic idea of the algorithm is as follows: the circular particles are randomly distributed in the rectangular matrix, but there is no contact between the particles, so a recognition area is set around each generated circular particle to prevent other particles from entering; if the newly generated circular particles do not contact with the previous circular (contained or intersected by the previous circular) and the circular particles are contained in the rectangular area, Then the particle is accepted, otherwise, the particle is discarded and a new particle is generated. When the circular particle meeting the conditions reaches the required area proportion, the algorithm is finished.

The cutter is simplified as a polygon with front and back angles, and the assembled multi-particle cutting assembly model is shown in Figure 1.



(a) Multi particle cutting assembly



(b) grid generation

Fig.1 Multi particle cutting assembly model and grid generation

The four node plane strain reduction integral element CPE4RT with good stability is used for the composite. In order to speed up the analysis and improve the accuracy, the cutting area is divided into a denser grid, the area far away from the cutting force is divided into a rarer grid. Considering that the rigidity of the tool material is greater than that of the material to be cut. In order to simulate this characteristic of the tool, the three node plane strain element CPE3T is selected when the tool is meshed. The meshed model is shown in Figure 1.

In the cutting process of particle reinforced composites, the interaction between tool and matrix material, tool and particle reinforced phase, SiC particles and matrix materials, SiC particles and SiC particles should be considered. In this two-dimensional cutting simulation, the workpiece is fixed by setting the left boundary, the lower boundary and the lower right boundary completely fixed constraints, as shown in Figure 2.

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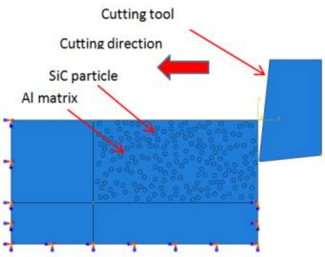



Figure 2 Boundary conditions and loading

## III. SIMULATION RESULTS

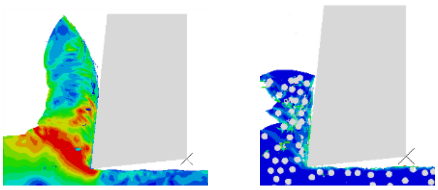
### *A. Surface morphology analysis*

The cutting simulation results of $SiC_p/Al$ composites are shown in Figure 3. There are many broken SiC particles and dislocations on the chip, leaving many grooves and holes on the machining surface. It clearly shows all kinds of defects caused by particles, such as voids caused by particles peeling, particles breakage, and particles pulling out, etc. It can be seen from the distribution of stress-strain field that the stress concentration at the interface between the particles and the matrix material is the main factor for the particles to peel off and produce cavities. The main reason for particle breakage is the irregular stress distribution caused by the violent interaction between the cutter, the particle and the matrix material. The scratches and pits on the workpiece surface may be caused by the rolling and sliding of the falling particles on the machined surface under the action of the cutter.

Fig.3 Simulation results of surface morphology

### *B. Chip shape analysis*

The simulated chip shape is shown in Figure 4. It can be seen that for 2024Al alloy, the chip formation process is a typical shear slip process. When the tool cuts into the workpiece and material reaches the yield strength limit, material flows from the separation layer to form chips. For the $SiC_p/Al$ composites, the matrix plastic deformation occurs under the cutting action of the cutter, deformation is hindered by the particles with high elastic modulus in the material transfer process, and the tearing position of the chip is in the matrix area around the particles. When the chip climbs along the front face, it will form a nodal chip along the micro crack due to the push of the tool.



a） 2024Al alloy b） $SiC_p/Al$ composites

Fig.4 Simulation results of chip morphology

### *C. Experimental verification*

In order to verify the results of the finite element simulation, SiCp/Al composites material was taken as the research object. On the CA6140 machine tool, the cutting speed v=50m/min, the rake angle $\gamma 0=6^{\circ}$ , the cutting depth ap=0.15mm were used to turn SiCp/Al composite material. The chip's side morphology was observed by the Kearns ultra depth of field microscope. The side morphology of the chip is shown in Figure 5.

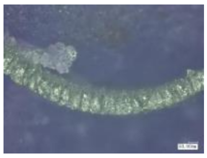


Fig.5 Actual chip morphology

Chip morphology can reflect cutting process to a certain extent. The chip morphology changes with the addition of hard particles in SiCp/Al composites. As can be seen from Fig. 6, the fluctuation of chips can be seen clearly from the chip side. The experimental results show that the chip of SiCp/Al composites is nodular, the simulation results are consistent with the experimental results.

## IV. CONCLUSION

Based on the finite element software ABAQUS and script language python, the micro structure model of $SiC_p/Al$ multi-particle random distribution is established to predict the machined surface morphology and chip morphology. The cutting simulation results show that the machining surface quality of $SiC_p/Al$ composites is poor due to the breakage and drawing of particles. Through the comparison between $SiC_p/Al$ composites and 2024Al alloy chip, it is found that 2024Al chip is more continuous, $SiC_p/Al$ Composites chip tends to be segmented. The experimental results show that the chip of $SiC_p/Al$ composites is nodular, experimental results of chip morphology prove the validity of the model.

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