Research on Cutting Forces of Ultra-Precision Cutting of Sicp/Al Composites

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Abstract. The ABAQUS finite element simulation software was used to establish a three-dimensional simulation model of ultra-precision cutting of SiCp/Al composites and dynamically simulate the change law of cutting force in the cutting process. Study the influence of cutting speed on the cutting force and the formation of the cutting surface. The simulation results show that with the increase of cutting speed, the maximum cutting force and the average cutting force increase. The influence of the change of cutting speed on the surface topography of the workpiece is studied. The results show that with the increase of cutting speed, the degree of particle breakage increases. Holes on the machined surface become larger and the dents deepen.

1. Introduction

SiCp/Al composites have many excellent physical and mechanical properties such as high strength and high wear resistance, making it highly popular in the fields of national defense and aerospace. These high-precision areas have strict requirements on the surface quality of parts. The surface quality not only affects the wear resistance and corrosion resistance of the parts, but also affects other properties such as dimensional stability [1, 2]. However, due to the presence of SiC particles in SiCp/Al composites, making the mechanical processing become difficult, which limits its application to a certain extent. Therefore, the research on the influencing factors of the surface quality has become the main content of SiCp/Al composites [3].

There are many factors influencing the quality of the machined surface. Cutting parameters, tool conditions, and the characteristics and distribution of SiC particles are the main factors [4]. Wang et al. designed the experimental study on the effects of cutting parameters on the surface roughness in terms of feed rate, cutting speed, cutting depth, and tool nose radius. It was found that the roughness influencing factors from large to small are cutting speed, feed, and cutting depth and arc radius [5]. Ge et al. experimented to verify the influence of cutting volume, particle volume fraction, size, tool crystal size, and cooling conditions on the quality of the machined surface. It was concluded that by increasing the cutting speed, using coolant, reducing volume fraction of reinforcement particle and decreasing the particle size can improve the surface quality [6]. Tang used single-factor analysis to study the effects of cutting speed, feed rate, axial cutting depth, and radial cutting depth on the machining quality, indicating the use of large cutting speeds, small feed rates, and radial cuttings deep equal or less than 4 mm can get better surface quality [7]. The above studies have shown that, in combination with other conditions, the cutting speed has an important influence on the surface quality of SiCp/Al composites.

The different crushing states of SiC particles in the process of SiCp/Al composites make the surface of the workpiece show different morphologies. In order to solve the problem that it is difficult to observe the surface morphology formation process in experiments, a three-dimensional simulation model of SiCp/Al composites was established by using Abaqus finite element simulation software, to study the influence of cutting speed on the particle action. The relationship between cutting speed and surface morphology was analyzed based on the change of cutting force in three directions.

2. Finite element model

A simplified model was used to simulate the process of face cutting. The dimension of cuboid workpiece is about in 0.48 millimeter long, 0.12 millimeter wide, and 0.1 millimeter thick. In the SiCp/Al composites, SiC particles were simplified into spheres with radius of 20 μm, and uniformly distributed in the workpiece, the volume fraction of reinforcement particle is approximately 17%.Since only the tip portion and the workpiece are in contact during the cutting process, sowing the tool with seed from compressed to sparse. The tool and workpiece assembly method is shown in Figure 1.

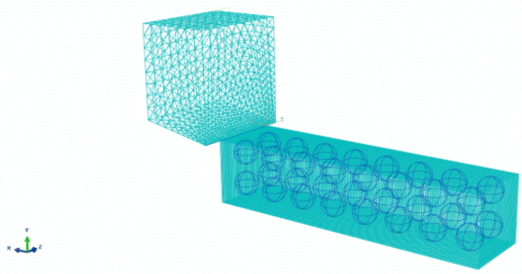


Figure 1. Finite element model.

In order to prevent the workpiece from moving during the cutting process, the six directions of the bottom of the workpiece are completely constrained. The tool is more rigid than the workpiece matrix, and this study does not consider the wear condition of the tool, so the cutter is set as rigid body. Set the tool and workpiece to face-to-face contact, the tool surface is set as the main contact surface, the friction formula is a penalty function, the friction coefficient is set to 0.25. A reference point is set on the tool, and the tool takes place along the negative direction of the X axis along the reference point.

In order to simulate the actual cutting process to the maximum extent, the aluminum matrix and the SiC particles are respectively assigned to the corresponding materials, and the tool adopts the PCD tool, which is currently considered the most competent in the SiCp/Al ultra-precision machining. The properties of these materials are shown in Table 1.

Table 1. Material properties.

Parameter	Young's modulus / GPa	Poisson's ratio	Density/ (T•mm^{-3})	Thermal conductivity /(mJ·mm· s·℃)	Coefficient of expansion	Specific heat capacity/(mJ·g·℃)
PCD	1147000	0.08	4.25E-9	2100	4E-6	525
Al alloy	70600	0.34	2.7E-9	180	2.36E-5	880
SiC	420000	0.14	3.13E-9	81	4.9E-6	427

Assumed the material to be isotropic and use the shear failure criterion to simulate the separation of the chip and the workpiece. The Aluminum alloy matrix uses the Johnson-Cook constitutive relation model to better express the viscoplasticity of the material, and the yield strength of the aluminum-based material is 265 Mpa. The strain rate sensitivity coefficient is 0.001, the strain enhancement coefficient is 426, the temperature sensitivity coefficient is 0.895, the strain hardening index is 0.183, the melting point is 923K, and the room temperature is 293K [8].

The single-factor analysis method [9] is adopted in the simulation, and only the cutting speed is changed. The simulation conditions such as other parameters remain unchanged. The details are shown in Table 2.

Table 2. Cut parameters

Cut condition	Cutting deep/mm	Cutting speed/(r/min)	Rake angle/°	Front angle/°	Tool nose radius/mm
Value	0.01	1000,1500,2000,2500	10	0	0.0003

3. Analysis of Cutting Force Simulation Results

Figure 2 shows the variation of the cutting force in the x-axis direction with the cutting path when the depth of cut is 10 μm.

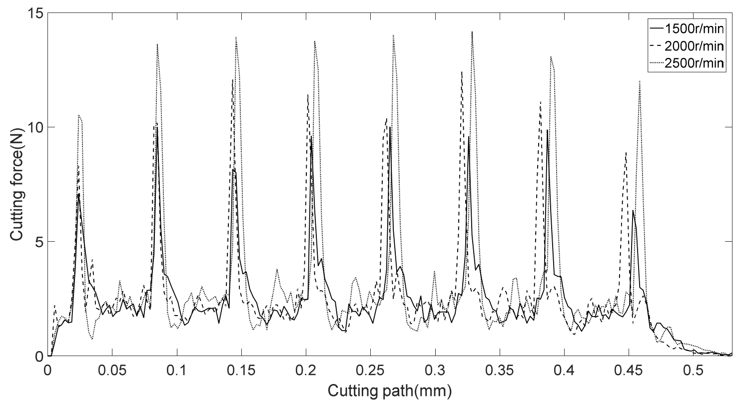


Figure 2. Effect of cutting speed on the cutting force in the x-axis.

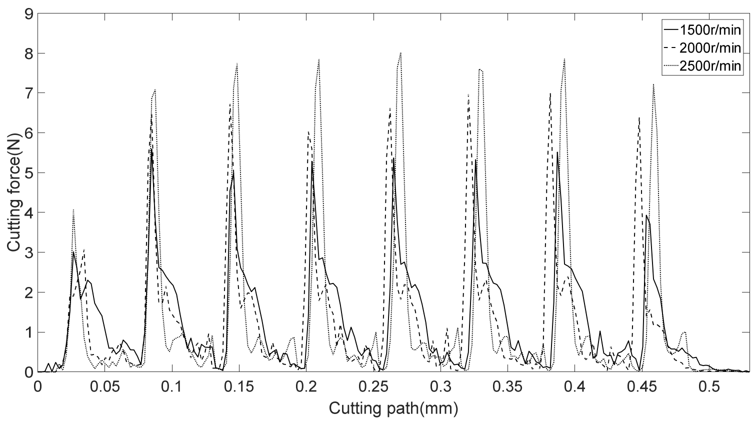


Figure 3. Effect of cutting speed on the cutting force in the y-axis.

IOP Conf. Series: Materials Science and Engineering **394** (2018) 032015 doi:10.1088/1757-899X/394/3/032015

The results show that the cutting force in the x-axis direction shows obvious periodic fluctuation, which is due to the uniform distribution of SiC particles in the matrix. After the contact between the tool and the SiC particles, the cutting force increases sharply in a short time and then decreases rapidly. The position of the wave crest on the cutting path varies with different cutting speeds, that is, the deformation of the matrix is different with the cutting of the SiC particles, which leads to the change of the maximum force position of the tool on the SiC particles, and the width of the wave decreases gradually as the cutting speed increases, that is, the relative path of the tool action on the SiC particles. As the distance decreases, the time of action also decreases. The cutting force of the tool and the aluminum base slightly floats around 2N, but as the cutting speed increases, the maximum cutting force of the cutter on the particles also increases.

The force perpendicular to the cutting surface also has a significant effect on the SiC particles. Figure 3 is an image in which the cutting force in the y-axis direction varies with the cutting path when the depth of cut is 10 μm. It shows that the force of the tool in the y-axis direction on the substrate also fluctuates periodically. The law is similar to the x-axis direction, but the force is about half of the force in the x-axis, and the width of the wave increases, indicating that the action time of the tool in the y-axis direction is greater than the x-axis, and the force in the y-axis direction is mainly manifested as the positive pressure on the SiC particles, so that the particles are easily pressed into the matrix material. The force in the z-axis direction appears as a line whose magnitude changes to zero along with the cutting path, and will not be described here.

In order to make a clearer analysis of the influence of different speeds on the cutting force, the average value of the maximum cutting force of the cutting tool on 8 particles is calculated. As shown in Figure 4, the average maximum cutting force increases with the increase of the cutting speed in the direction of X and Y axes, and the increasing rate of the X axis is slightly greater than that of the Y axis.

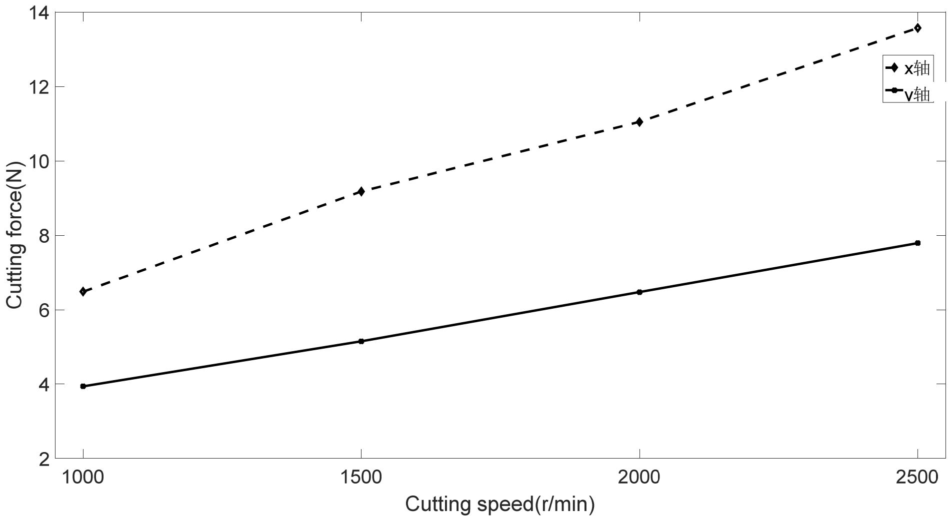


Figure 4. Average maximum cutting force with different cutting speed.

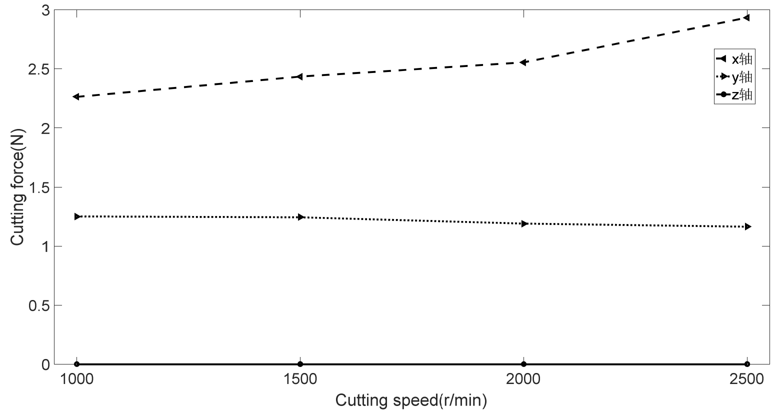


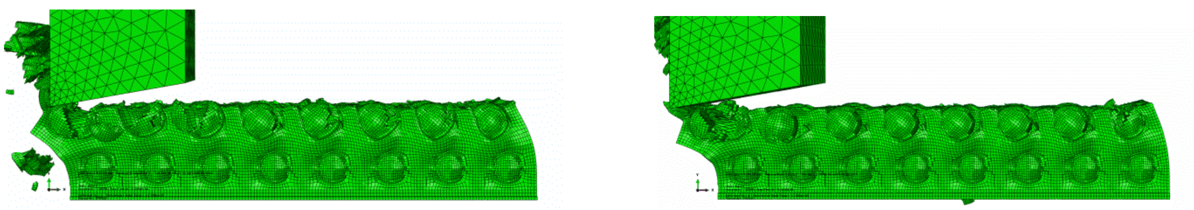
Figure 5. Average cutting force with different cutting speed.

Figure 5 shows the average value of the forces in the directions of x, y, and z as a function of cutting speed for the entire cutting process. From Figure 5, it can be seen that as the cutting speed increases, the cutting force in the x-axis direction gradually increases. The cutting force of the Y axis decreases slightly with the increase of the velocity, which is the opposite to the change of the average maximum cutting force. The reason is that with the increase of the cutting speed, the time of the tool action on the SiC particles is less. The average cutting force in the z-axis direction is maintained at 0N. The influence of cutting force in the z-axis direction on the ultra-precision cutting of SiCp/Al composites is almost negligible.

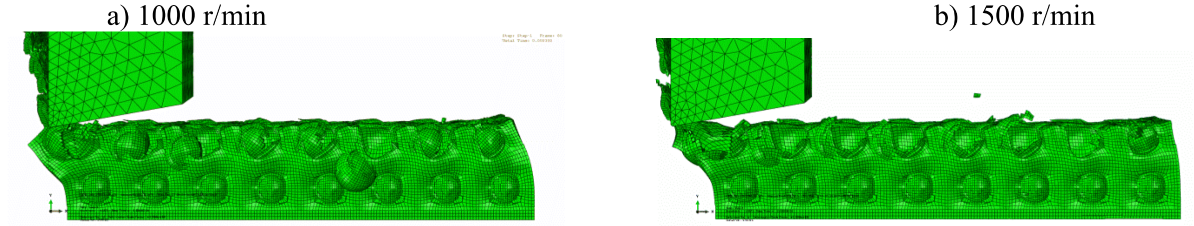
The above results show that when the speed is low, the force of the tool on the particles is small, the action distance is long, and the plastic deformation caused by the squeezing action of the particles on the workpiece is small; when the cutting speed is large, the cutting force is large, and the cutting distance is short , The cutter has obvious effect on the squeezing of particles, the volume of surface cavities increases, the degree of cracking of the particles increases, and the sag deepens.

4. Analysis of surface morphology simulation results

At different cutting speeds and the same cutting depth, the surface of the workpiece after ultra-precision machining presents different surface topography. The Remove Selected option is used to remove part of the matrix, enabling the complete representation of the internal conditions of the workpiece and dynamically displaying the particle breakage process during the cutting process. The profile of the workpiece at four cutting speeds are shown in Figure 6, cutting depth is 10 μm.



a) 1000 r/min b) 1500 r/min



c) 2000 r/min d) 2000 r/min

Figure 6. Surface Profile with different cutting speed.

IOP Conf. Series: Materials Science and Engineering **394** (2018) 032015 doi:10.1088/1757-899X/394/3/032015

Through the cross-section, the changes of SiC particles inside the workpiece after processing can be observed clearly. Compared with the above four figures, it can be clearly seen that the SiC particles show different shapes at different cutting speeds. Figure 6 (a) shows that when the cutting speed is 1000r/min, SiC particles are tilted to a certain degree along the cutting speed direction, and the upper part of the particles is slightly broken. As the tool moves, the fracture condition is aggravated and the smaller holes are formed on the workpiece surface. Figure 6 (b) shows that SiC particles also tilt when the cutting speed is 1500r/min. However, unlike Figure 6 (a), after the particles rotate, a large gap is formed between the lower right part and the substrate, which increases the volume of the cavity on the surface of the workpiece. Under the action of the cutter and the adhesion between the particles and the substrate, the bond between the particle and the substrate is torn. The particle morphology in Figure 6 (c) is varied. Compared with Figure 6 (a) and 6 (b), the fracture of the particles is more obvious, and the particles are trapped in the aluminum base in the direction of the cutting speed, the cavity volume increases and the spherical pits are produced. Figure 6 (d) shows that when the cutting speed is 2500r/min, a large number of pits are formed on the surface of the workpiece, mainly due to the rupture of the SiC particles. The cutter removes the debris in the middle of the granules, and the rest is embedded in the matrix.

5. Conclusion

(1) A three-dimensional simulation model of ultra-precision cutting SiCp/Al composite material was established, and the variation law of cutting force was simulated dynamically;

(2) When cutting the SiC particles, the cutting force increases significantly, and since the distribution of SiC particles in the workpiece, cutting force presents periodic fluctuations;

(3) As the cutting speed increases, the cutting force increases, the SiC particle crushing degree increases, the cavity volume on the machined surface becomes larger, and the sag deepens.

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