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Procedia CIRP 45 (2016) 211 – 214

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3rd CIRP Conference on Surface Integrity (CIRP CSI)

An Investigation of Surface Defect Formation in Micro Milling the 45% SiCp/Al Composite

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Abstract

In this paper, an orthogonal cutting simulation on machining 45% SiC/Al composites is presented for develop an in-depth understanding of surface defects in micro milling of the SiCp/Al composites and the associated machining parameters. PCD micro end mill is used with the value of the cutting edge radius close to the SiC particle size. The material removal mechanism and the surface defect formation at three typical cases are analysed. The results indicate the main machined surface defect is affected by the tool-particle interaction location. The half interaction location might lead to the best surface quality, which is proved by cutting trials and experimental observation.

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Keywords: Simulation; SiCp/Al composites; Micro milling; Surface defect

1. Introduction

Nowadays, particulate silicon carbide-reinforced aluminum matrix composites (SiCp/Al) have attracted considerable interest because of its light weight, good fatigue properties, dimensional stability at elevated temperatures, and high wear resistance over common alloys [1,2]. However, because of the hardness of SiC particles and softness of Al matrix, the machining of the composites is very challenging and each machining process leads to different surface defects [3].

Simulation study of the machining of the composite is a very effective way to understand the removal mechanism. Ramesh et al. [4] analyzed the normal and shear stresses for the possible four encounters of the tool with the matrix, based on the FE analysis of diamond turning of the SiCp/Al6061 composites. Pramanik et al. [5] investigated the matrix deformation and tool-particle interactions during machining by using Ansys/LS-Dyna. Zhou et al. [6] analyzed the removal mechanism of the SiC particles and the von Mises equivalent stress distributions of particle and matrix at different cases using a micro-FE model. Umer et al. [7] investigated the interface between particles and the matrix by using two approaches (with and without cohesive zone elements). The local effects, such as tool-particle interaction and particle debonding, are simulated. Dandekar et al. [8] predicted the subsurface damage and particle-matrix debonding after machining by using a two-step 3D model by AdvantEdge and Abaqus/Explicit.

The simulation results described above provide an insight for the interaction among tool, matrix and particles and understanding of the removal mechanism. However, the tools they used are often considered total sharp or nearly totally sharp, which means the tool edge radius is much smaller than the particle size. Meanwhile, the particles in their model are usually treated as an isotropic perfectly elastic material. Recently, Wang et al. [9] built a 2D simulation on defect formation mechanism of the machined surface in milling of high volume fraction SiCp/Al. Using the round and polygonal particles mode, simulations were made without and with SiC particle fracture respectively and surface defects were particularly analyzed. However, the tool edge radius is 5μm, larger than most particles, and the cutting parameters' effect is not considered in the analysis.

In this paper, a 2D micro-FE model was developed using ABAQUS/Explicit to analyze the removal mechanism and surface defects of 45% SiCp/Al composites with the value of the tool edge radius close to the SiC particle size. Interaction location between the tool and particles is categorized into

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doi:10.1016/j.procir.2016.02.327

three cases: tool facing the upper, the middle, and the lower of SiC particle, respectively. The three cases are simulated and analyzed respectively. The feed rate is analyzed to make a relationship between simulation and experiment, and the surface roughness is used for verification.

2. Simulation model

The cutting mechanism of the orthogonal cutting process can be used to describe the micro milling with large depth [9]. Therefore, a 2D orthogonal cutting model with a SiC particle in Al2024 matrix is established by employing ABAQUS. The Al matrix and SiC particle are modeled separately and assembled together. The selected dimension in simulation is: mm-N-t-s-MPa-˚C.

In terms of the interface, the particle and the matrix are tied together to make their initial displacements equal. In this paper, we regard the failure of the tie constraint between the particle and the matrix as the debonding phenomenon.

In the workpiece, the volume of SiC particle accounts for 45% and Al accounts for the rest. The cross section size of the workpiece is 7μm*6.2μm. The SiC is a spherical particle with radius 2.5μm. The rake angle of the PCD tool is 0˚ and the relief angle 15˚. The edge radius is 1.0μm, which is close to the size of SiC particle.

The FE model of SiCp/Al composites is shown in Fig. 1. The dynamic, temp-disp, explicit step is selected and Free Mesh technology is mainly used for the Al and SiC particle, with grid CPE4RT units. Triangle Mesh technology is used for the PCD tool with grid CPE3T units. Considering the high hardness of the PCD, the tool is set as a rigid body.

As Fig. 2 shows, in order to make an in-depth understanding of the defect formation mechanism, different tool-particle interaction positions are categorized into three cases: (a) tool cutting the upper of the SiC particle; (b) tool cutting the middle of the particle; (c) tool cutting the lower of the particle. In all simulations, the composite is constrained against movement in any direction at the bottom, left-hand half side, and the lower portion of the right-hand side.

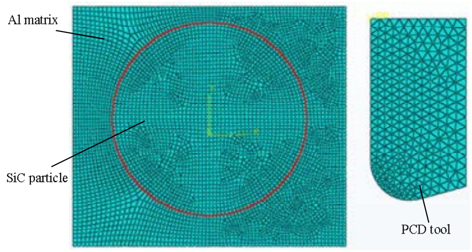

Fig. 1. FE analysis model of micro milling SiCp/Al composites.

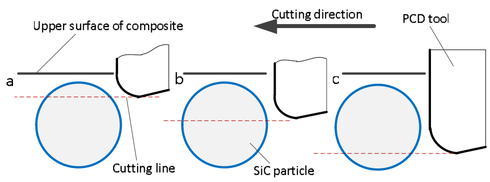

Fig. 2. Interaction locations between the tool and particles: (a) tool faces the upper of SiC; (b) tool faces the middle of SiC; (c) tool faces the lower of SiC.

3. Material properties and chip separation criterion

The elastic behavior of the Al2024 and SiC material are specified by providing the Elastic modulus and Poisson's ratio, which are listed in Table 1. Al is a typical elastic-plastic material, and the Johnson-Cook plasticity model is usually utilized for its plasticity behavior. The model equation is represented by Eq. (1).

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

Where ε 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 are the current temperature and material melting temperature, respectively. T_r is the room temperature. A, B, C, m are material constants and n is the strain hardening index.

In addition, in this study, in order to achieve chip separation during the cutting, the Johnson-Cook damage law [10] is used for the simulation of the Al matrix failure.

SiC is a kind of brittle material whose characteristics are different from Al, so brittle cracking model in Abaqus is used. The SiC particle is modeled as perfectly elastic material with the fracture energy cracking, which can be used to simulate the most brittle materials and allows the unit to be removed [11,12]. The parameters used in the models are shown in Table 1 and Table 2.

The surface to surface contact is defined between rake and flank surfaces of the tool and matrix nodes as well as the tool surfaces and particle nodes. Coulomb friction model is used in contact definitions. The constant friction coefficient used in this paper is 0.35 [9].

During the process of simulation of the cutting, there are three kinds of separation criteria: shear failure criterion, element deletion and adaptive grid technique. In this paper the element deletion technique is used, namely when the grid unit is failed, it will automatically be deleted.

Table 1. Material properties of the Al2024, SiC and PCD [6, 10].

Material	Al2024	SiCp	PCD
Density ρ(g/cm^3)	2.77	3.13	4.25
Elasticity modulus E(GPa)	73	427.5	1147
Poisson ratio v	0.33	0.14	0.07

Table 2. Plastic property parameters of the Al matrix [10].

A(MPa)	B(MPa)	C	m	n	T_m(˚C)	T_r(˚C)
369	684	0.0083	1.7	0.73	502	20

4. Simulation Results and Analysis

4.1. Case a

In this case, center of the SiC particle is below the cutting edge. Fig. 3 shows the stress distribution in Al matrix. It shows that the maximum stress reached 949.7MPa in Al. In this zone Al matrix occurs plastic deformation until the chip appears and separates from workpiece.

Because of the extrusion between the tool and matrix and the high hardness of SiC, the interface between matrix and particle (the tie constraint) is failed, shown in Fig. 4. We can regard that as the interface debonding phenomenon.

When tool cuts the particle, the von Mises stress dramatically increases. Fig. 5(a) shows that the maximum stress in particle reached 20.93GPa which is higher than the ultimate strength of SiC, and the particle will undergo brittle fracture. As shown in Fig. 5(b), along with tool's movement, the particle fractures and crack occurs. Due to the hardness of SiC, the particle has a distinctly downward movement and is pressed into the matrix a little during the process.

In this case, surface defects mainly include the SiC particle's brittle fracture, being pressed into matrix and burst because of the crack penetration.

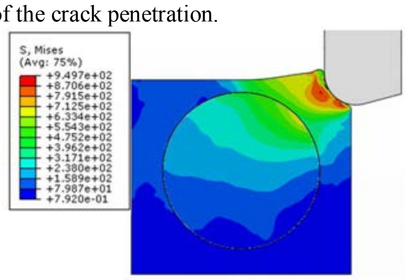

Fig. 3. Stress distribution in the Al matrix

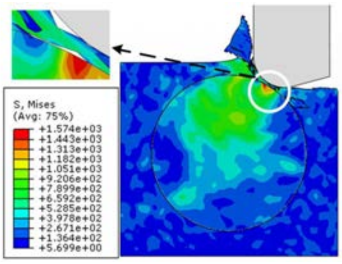

Fig. 4. Interface debonding phenomenon in case a

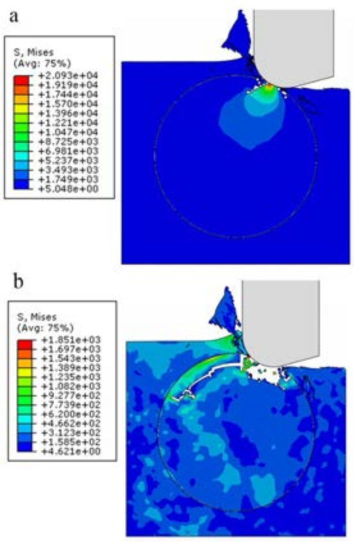

Fig. 5 The brittle cracking of the SiC particle and surface defects

4.2. Case b

In this case, the cutting edge is around the center of the SiC particle. Fig. 6 shows the failure of the tie constraint between matrix and particle. Due to the plastic property of Al and extrusion of the tool, the Al elements around the cutting line are squeezed into the upper and the below sides, and the tie fails, where we can think the interface debonded. Meanwhile, the interface around the upper side fails more dramatically than it around the below side. Fig. 7 shows that along with the tool movement, the interface around the upper side fails quickly and the chip generates with the particle's brittle fracture.

Because of the large edge radius of the tool tip, the Al matrix may be adhered to the tool flank face and cover the machined SiC material and cracks, reducing the surface defects and improving the surface quality.

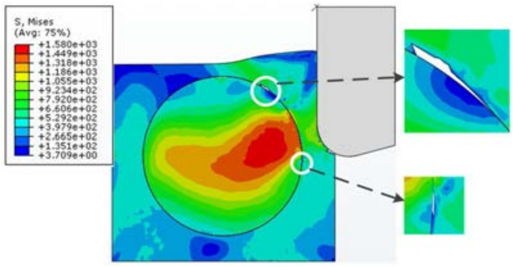

Fig. 6. Interface debonding phenomenon in case b

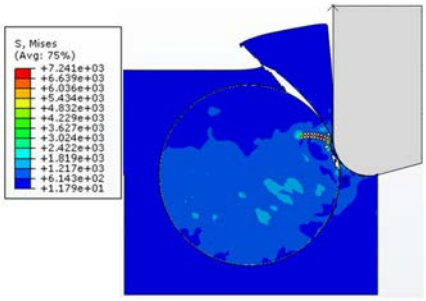

Fig. 7. Chip generation and brittle cracking of SiC particle

4.3. Case c

In this case, the cutting edge is located below the center of the SiC particle. The surface quality is poor in this condition. As shown in the Fig. 8(a), at the early stage of the interaction between the tool and the Al matrix, the tie constraint between the matrix and the particle around the bottom fails and we can regard that as the interface debonding phenomenon. Along with the tool's movement, the debonding phenomenon becomes more dramatic. Finally, most parts of the interface fail, especially the parts around the bottom of SiC particle edge. The particle is pulled out and a pit hole may be created at the machined surface. Meanwhile, due to the extrusion between the tool and the workpiece, a little brittle fracture might be observed in the SiC particle, shown in Fig 8(b).

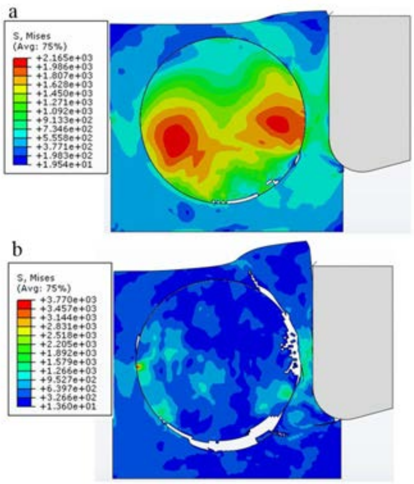

Fig. 8. The interface failure and surface defects in case c: (a) the debonding phenomenon; (b) pulling out of the particle

5. Experiment and analysis

According the simulation, different tool-particle interaction location may cause explicitly different surface topography and surface detects. Considering the cutting depth is related to the feed per tooth in milling [9,13], three different values of feed per tooth (f_z) are chosen for the experiment. The roughness R_a (arithmetical mean deviation of profile) and R_z (ten-point height of irregularities) are measured and compared.

A dry machining experiment is conducted on KERN EVO, and a single flute ϕ1mm PCD end mill (Shenzhen Oupeite Company, China) is used. The tool rake angle is 0°, the clearance angle is 15° and the cutting edge radius is 1μm. The 45% volume fraction SiCp/Al composite is used for the workpiece, in which the average particle size is 5μm.

Spindle speed keeps 20000rpm, milling depth keeps 100μm, cutting width is 0.5mm, and up milling is used. The three values of f_z are 0.5μm/z, 2.0μm/z, and 3.5μm/z. Surface roughness of the side wall is measured using Taylor Hobson Form Talysurf. Finally, the values of R_a and R_z are shown in Table 3.

Table 3. The experiment results

Feed per tooth f_z (μm/z)	0.5	2.0	3.5
R_a (μm)	0.4490	0.2849	0.7903
R_z (μm)	1.2507	0.6943	1.8540

From the Table 3, we can see that both R_a and R_z reach their minimum values when f_z is 2.0μm/z, which is around the half of particle size. When feed per tooth is 3.5μm/z, R_a and R_z both get their largest values. The results partly show that the surface quality is improved with a feed per tooth whose value is around the half of SiC particle size.

6. Conclusions

Micro cutting FE model and simulation are developed for investigating the materials removal mechanism and the machined surface defect formation particularly in micro milling the 45% SiC/Al composites. The key conclusions can be drawn as follows:

- The removal mechanism and the surface defect associated with SiC particles depend on the tool-particle location and brittle fracture of SiC. The debonding phenomenon can be seen in all cases. When the tool faces the upper (case a) or the middle (case b) of SiC particle, the particle would be mainly cut off by brittle fracture. Particle depression, crack penetration and burst might be major defects in case a; while the defects might be reduced because of the coating of Al matrix in case b. When the tool encounters the lower of the particle (case c), the particle would be more likely to be pulled out and pit holes are formed on the surface.
- The micro milling feed per tooth value is recommended to be close to the half of the particle size. When the feed rate is around that value, a good surface with small roughness might be produced.

Acknowledgements

Authors would like to acknowledge the partial funding support from the State Key Lab of Digital Manufacturing Equipment & Technology (Project No.: DMETKF2015004) for this research work.

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