Investigation on the removal characteristics of single-point cutting high-volume fraction SiCp/Al composites

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Abstract
SiC-reinforced aluminum matrix composites (SiCp/Al composites) are typically difficult-to-machine material, and the irregular SiC diffused in SiCp/Al composites make the surface quality worse. In this paper, a single-point cutting simulation with variable plane cutting depth were conducted for SiCp/Al composite with higher volume fraction (65 Vol%) and aluminum alloy. The surface morphology characteristics of SiCp/Al composites, which mainly include breaking, part breaking, pulling out, protruding, al tearing, and interface debonding, are different from those of aluminum alloy materials. The high-volume SiC lower the surface quality and profile dimensional accuracy of SiCp/Al composites. There are thin and discrete layers covered on the machined surface. Finally, a single-point cutting test, which meets the actual grinding condition, was conducted for 2A12 aluminum alloy, 45% SiCp/Al composite, and 65% SiCp/Al composite. The simulation results are verified by experimental data obtained from the single-point cutting test.

Keywords SiCp/Al composites · Removal characteristics · Finite element model · Cutting mechanism · Surface quality

1 Introduction
SiCp/Al composites with high SiC volume fraction have excellent physical and mechanical properties, including high specific strength, high specific modulus, good wear resistance, high temperature resistance, low thermal expansion coefficient, and good dimensional stability [1–3]. SiCp/Al composites are widely used in the aerospace industry, automotive industry, electronics industry, and other fields [4–6]. However, due to clustering and non-homogeneous distribution of hard SiC in the ductile aluminum alloy matrix, SiCp/Al composites have poor machinability. Both failure criteria and mechanical behaviors are different from homogeneous materials during the machining process. The material is a kind of typical difficult-to-machine material, which is easy to cause numerous surface defects and rapid tool wear rate in cutting process [7–11]. All of these make the machining of SiCp/Al composites challenging. Therefore, the study on cutting characters of SiCp/Al composites has become a hot spot.

At present, numerical modeling has been used by many researchers as a tool to understand the SiCp/Al composites removal mechanisms associated with machining processes. Wang et al. [12] studied the influences of fracture and removal mechanism of SiC on surface generation using a three-dimensional (3D) finite element model of turning. It was found that the manners of SiC particulate removal have an important influence on surface generation. Liu et al. [13] and Wu et al. [14] using the finite element models studied the material removal mechanism and defect formation mechanism of SiCp/Al composites considering tool and SiC interaction in different positions. The results showed that the major material removal form of SiC is brittle fracture and pulling out base on the different area of SiC in contacting with the tool. Xiang et al. [15] combined turning finite element analysis with ultrasonic-assisted milling experiment and found that the application of ultrasound improved the particle rupture effect. Appropriate ultrasonic amplitude inhibited the particle breakage and slowed down the crack growth. A smoother particle breaking phenomenon was observed with the application of a higher frequency. Wang et al. [16] investigates the underlying...
The single-point cutting test is an effective method to study the removal characteristics of particle-reinforced metal matrix composites. Yan et al. [17] studied the cutting mechanisms and the relationship between specific energy of scratching and depth of cut (size effect) on the low volume fraction (10–20%) composites reinforced by $\text{Al}_2\text{O}_3$ and SiC ceramic particles by single-point cutting test. The results indicated that the scratch process was composed of rubbing, plowing, and plastic, and for machining MMCs, a larger depth of cut should be used to maintain a lower machining energy, especially for those with a larger ratio of volume fraction of particle radius. Feng et al. [18] and Zha et al. [19] studied the scratch load, coefficient of friction (COF), and scratch morphology on 55% SiCp/Al composites by comparing the ultrasonic vibration-assisted scratch (UVAS) and traditional scratch tests. The results indicated that the ultrasonic vibration played an important role in reducing the grinding force and COF, as well as improving the morphology of the machined surfaces.

There is very little literature regarding the single-point cutting of higher volume fraction (greater than 55%) SiCp/Al. Most researches focus on plane turning, and there is a lack of research on plane grinding. The volume fraction increasing makes the grinding process more complicated. The material grinding removal mechanism of high volume fraction SiCp/Al composites still need further study. The grinding material removal process is difficult to be directly observed due to the random distribution of different sized abrasive particles. Therefore, the single-point cutting test with variable plane cutting depth was proposed to simplify the grinding process in this paper so that the material grinding removal mechanism can be better revealed. Furthermore, the finite element simulation can be used to reveal the material removal process in microscopic view and the elastic, plastic deformation, and fracture process of SiCp/Al composites can be revealed.

In this paper, the single-point cutting simulations with variable plane cutting depth were realized to study the grinding process and the surface formation processes of 2A12 aluminum alloy and SiCp/Al composite with higher volume fraction (65 Vol%) were studied. Compared with aluminum alloy, the cutting property and surface generation characteristics of 65% SiCp/Al composites were revealed. Furthermore, a single-point cutting test method, which meets the actual grinding conditions, was proposed to verify the simulation. Finally, the simulation results are verified by experimental data obtained from the single-point cutting test of 2A12 aluminum alloy, 45 Vol% SiCp/Al, and 65 Vol% SiCp/Al composite.

### 2 SiCp/Al composite removal model

#### 2.1 Finite element model

A microstructure-based two-dimensional plane strain and random particle single-point cutting model was built with Abaqus/Explicit by imitating the real particle morphology from typical micrographs of 65%SiCp/Al composites, as shown in the upper half of Fig. 1. In this model, the volume fraction of SiC particle in SiCp/Al composites is 65% and the SiC exhibited an average size of about 40 μm. The workpiece length and height are 1.6 mm and 0.4 mm. The cone vertex angle and radius of the single diamond grit is 120° and 0.2 mm, respectively. The cutting speed is 5.26m/s, and the cutting path is a circular arc. The maximum cutting depth 20 μm is available in the bottom of the circular arc. It can also be seen that the morphology of the SiC, which agrees with typical micrographs of 65%SiCp/Al composites, is polygonal, including quadrilateral, pentagon, and hexagon. In order to simplify the algorithm, the volume fraction is defined as the ratio of the sum of polygon areas and workpiece area. The model of the workpiece is generated by a custom subroutine which can automatically build a model of a workpiece by setting some model parameters, such as SiC shape, diameter, and volume fraction. The custom subroutine also enables random distribution of particles in the matrix. In the simulation, the random distribution of particles can truly reproduce the microstructure of the composite; the interaction between particles can also be fully considered [20]. In this model, the matrix and the particles were modeled separately and the 4-node plane strain bi-linear quadrilateral elements (CPE4RT) in ABAQUS were adopted to mesh both the matrix and SiC. The global element size of 0.0055 [21] mm was selected due to the better computational efficiency and more accurate cutting force estimation. Since the interface is very hard and brittle and hence similar to the particles [22], the interface was considered as an extension of the particle. The particle and the matrix are tied together so that their initial displacements at the interface are equal. The interfacial debonding is achieved through the failure of the matrix material which is also used by other researchers [23–26].

The tool used in this experiment is a standard diamond indenter, and it is simplified in the simulation. Because the tool has the characteristics of high hardness, strength, wear resistance, and high temperature resistance, less deformation occurred during the machining process. It is established to the rigid body, to improve the calculation efficiency. And the reference point is set on the tool to control the tool cutting path and output the cutting force and other parameters. Penalty contact between the cutting tool with matrix and particles is defined with the aim of enabling the tool-particle interaction. The workpiece is constrained at the bottom and side surface. Furthermore, a two-dimensional plane strain
model of aluminum alloy (0 Vol%) was also built to compare with the SiCp/Al composites (65 Vol%), as shown in the bottom half of Fig. 1. The main difference between the model of 2a12 aluminum alloy and SiCp/Al composites is whether the workpiece contains SiC or not. Through comparative analyses of material removal processes, the influence of SiC on surface generation of SiCp/Al composites can be revealed.

In this work, the single-point geometric parameters, cutting path, maximum cutting depth, cutting speed, average particle size, volume fraction, and so on are all comparable to the experimental data.

2.2 Material constitutive equation

Aluminum alloy has flow characteristics and is greatly influenced by strain, strain rate, and high temperature. Johnson–Cook constitutive equation includes those influence factors. Thus, it can well simulate the cutting process of matrix materials in practice. In this work, the Johnson–Cook constitutive equation was implemented to model the flow behavior of Al alloy. Here, the Johnson–Cook model can be expressed as:

$$\sigma = A + B\varepsilon^n \left[ 1 + C \ln \left( \frac{\varepsilon}{\varepsilon_0} \right) \left[ 1 - \left( \frac{T-T_r}{T_m-T_r} \right)^m \right] \right]$$

where $\sigma$ is the flow stress, $A$ is the yield stress at reference temperature and strain rate, $B$ is the strain hardening coefficient, $\varepsilon$ is the plastic strain, $n$ is the strain hardening exponent, $C$ is the strain rate sensitivity coefficient, and $m$ is the thermal softening exponent, $T$ is the strain rate, $\varepsilon_0$ is the reference plastic strain rate. $T_r$ is the workpiece temperature, and $T_m$ and $T_r$ are the material melting and room temperature, respectively.

The material constants of 2A12 Al alloy matrix are obtained from the split Hopkinson pressure bar (SHPB) test over wide temperatures and strain rates by Li [27] and listed in Table 1. The material parameters of Al alloy matrix and silicon carbide applied in the finite element computational analysis are listed in Table 2 [27–29].

2.3 Fracture criterion of matrix material

Liu et al. [30] found that the simulation results agreed well with the experiment results of the metal cutting process when using the Johnson–Cook damage criterion including the failure evolution model. Thus, in this work, Johnson–Cook damage criterion was utilized to describe the chip separation behavior for all the Al alloy matrix elements. Johnson–Cook criterion for damage initiation is met when the following condition is satisfied [31]:

$$w_D = \sum \frac{\Delta \varepsilon^p}{\varepsilon_f} = 1$$

$$\varepsilon_f = [d_1 + d_2 \exp(-d_3 \eta)] \left[ 1 + \ln \left( \frac{\sigma}{\sigma_0} \right) \right] \left[ 1 + d_5 \left( \frac{T-T_r}{T_m-T_r} \right) \right]$$

Here, $w_D$ is scalar of failure state, $\Delta \varepsilon^p$ is the change in the equivalent plastic strain during each integration cycle, $\varepsilon_f$ is the fracture strain, $d_1 - d_5$ are the failure parameters of matrix materials, $\eta = p/q$ is the stress triaxiality, $p$ is the pressure stress, $q$ is the von Mises equivalent stress, and $\varepsilon_0$ and $\varepsilon_f$ are

| Table 1 Material constants for Johnson–Cook constitutive model of the 2A12 Al alloy |
|-------------------------------------|-----------------|----------|----------|---------|----------|
| $A$ | $B$ | $n$ | $C$ | $m$ | $T_{\text{mat}}$ |
| MPa | MPa | | | | K |
| 370.4 | 1798.7 | 0.73315 | 0.0128 | 1.5282 | 863 |
2.4 Fracture criterion of SiC material

In this paper, the brittle fracture criterion was added into the material property of SiC to simulate the cracking of SiC in cutting process. SiC are hard and in elastic state before fracture, and the relationship of stress and strain obeys the generalized Hook's Law, and brittle cracking model was used. The failure parameters $d_1 - d_5$ applied in the Abaqus/Explicit are listed in Table 3 [29].

A function of the crack opening strain about the shear retention factor of material, which can be calculated by the following formula:

$$\rho(e_{mn}^{ck}) = \left(1 - \frac{e_{mn}^{ck}}{e_{mn}^{max}}\right)^p$$

Here, $G_s$ is the shear modulus of the undamaged material, and $\rho(e_{mn}^{ck})$ is the shear retention factor of material, which can be calculated by the following formula:

$$G_s = \rho(e_{mn}^{ck}) G$$

Here, $G$ is the shear modulus of the undamaged material, and $\rho(e_{mn}^{ck})$ is the shear retention factor of material, which can be calculated by the following formula:

$$\rho(e_{mn}^{ck}) = \left(1 - \frac{e_{mn}^{ck}}{e_{mn}^{max}}\right)^p$$

The friction between the tool and the workpiece has great effect on cutting force and cutting temperature, thus affecting the surface integrity. Therefore, the selection of friction model is very important for guaranteeing a high-quality calculation. The chip of high-volume fraction SiCp/Al composites has high brittleness, and the tool-chip relative sliding is more remarkable than tool-chip coalescence. Therefore, coulomb friction model is applied into the interaction between the tool and the matrix material as well as the tool and SiC. The formula can be expressed as:

$$\tau = \mu P$$

Here, $\tau$ is friction force, $\mu$ is coefficient of sliding friction, and $P$ is positive pressure. A constant Coulomb friction coefficient of $\mu = 0.5$ is used in all simulations since it represents a sliding contact condition between the tool and the workpiece [33].

2.6 Simulation results of single point cutting

Aluminum alloy has good plasticity and low hardness while SiC is hard and brittle. SiCp/Al composites contain both aluminum alloy and SiC, which makes the cutting process complex. Especially for high-volume fraction SiCp/Al composites, the cutting characteristics need to be further revealed. Thus, single-point cutting simulation was carried out.

| Table 2 | Material parameters of the 2A12 Al alloy and SiC |
|---------|---------------------------------------------|
| $E$, Young's modulus (GPa) | 71.7 | 420 |
| $\mu$, Poisson's ratio | 0.33 | 0.14 |
| Coefficient of thermal expansion (K$^{-1}$) | $26.6 \times 10^{-6}$ | $4.9 \times 10^{-6}$ |
| $\rho$, density (kg·m$^{-3}$) | $2.77 \times 10^3$ | $3.13 \times 10^3$ |
| $k$, thermal conductivity/(W·m$^{-1}$·K$^{-1}$) | 175 | 81 |
| C, specific heat/(J·kg$^{-1}$·K$^{-1}$) | 921 | 427 |

| Table 3 | Johnson-Cook damage parameters of the 2A12 Al alloy matrix |
|---------|--------------------------------------------------|
| $d_1$  | 0.116 |
| $d_2$  | 0.211 |
| $d_3$  | $-2.172$ |
| $d_4$  | 0.012 |
| $d_5$  | $-0.01256$ |

| Table 4 | Parameters of the material fracture model |
|---------|-------------------------------------------|
| $\sigma_b$ (Mpa) | $G_f$ (J/m$^2$) | $\mu$ | $e_{max}^{ck}$ |
|----------|------------|------|----------------|
| 1500     | 30         | 1    | 0.001          |

cook
out on the three materials for revealing the influence of volume fraction on cutting quality through comparative analyses.

Figure 2 shows the surface topography of aluminum alloy after single-point cutting simulation. It can be seen that aluminum alloy has good surface integrity and no defects like pits or cracks after cutting. Furthermore, there are only plastic deformation and few scales, and the fluctuation of the contour is small.

Figure 3 shows the surface topography of 65% SiCp/Al composites. It can be found that the high-volume fraction of SiC increases the brittleness of material and the material surface has defects like interfacial debonding (Fig. 3a), protruding (Fig. 3b), pulling out (Fig. 3c), crushing (Fig. 3d), part crushing (Fig. 3f), al tearing (Fig. 3e) and so on. As a whole, the cutting surface presents an uneven surface topography, including pits, protruding and plastic deformation, severely affecting the surface quality. The cutting surface of SiCp/Al composites is very different from aluminum alloy. The addition of SiC changes the material removal mechanism. There are both plastic failure of aluminum matrix and brittle failure of SiC in the failure procedures of SiCp/Al composites. Furthermore, because of the high hardness of SiC, it generates pushing effect on aluminum alloy, causing the appearance of micro-cracks and deformation on the surface topography.

Comparing the surface topography of 65% SiCp/Al composites and aluminum alloy, we can infer that the increase of volume fraction of SiC will decrease the surface quality of cutting. We will conduct experiments on different volume fraction SiCp/Al composites to confirm the inference in the following sections.

3 Single-point cutting experiment

In order to reveal the material removal characteristics, single-point cutting experiments were carried out on aluminum alloy and 65% SiCp/Al composites. The scratch appearance and micro morphology were observed, and the characteristics of material failure were analyzed.

3.1 Pretreatment of materials

The materials used in the experiments were 2A12 aluminum alloy, 45 Vol% SiCp/Al, and 65 Vol% SiCp/Al composites. Specifically, the 2A12 aluminum alloy and 65 Vol% SiCp/Al composites aim to verify simulation results. The 45 Vol% SiCp/Al is further used to confirm the inference that the increase of volume fraction of SiC will decrease the surface quality of cutting, which is inferred from simulation results.

In order to reduce the effects of surface roughness and residual stress on experimental results, rotation and gravity type of grinding-and-polishing machine was utilized to grind and polish the materials. The average roughness of all test workpieces are less than 0.05 μm after the pretreatment and the surface topography pictures were shown in Fig. 4.
3.2 Experimental details

The experiments were carried out on CNC drilling and milling test bench, and the testing apparatus is shown in Fig. 5. We adjust the position of the workpiece in fixture by trial cutting and make the final position of scratch be in the middle of the workpiece. Further, due to the length of scratch is much less than the length of the workpiece, the inclination of the workpiece has a small impact on the maximum cutting depth. By using the dial indicator, we ensure that the inclination of workpiece is about 3 \( \mu \)m, which is enough to ensure the effectiveness of our experimental result. Besides, the tool setting accuracy of our machine tool is 1 \( \mu \)m, which can further ensure the effectiveness of our experimental result.

It can be seen that the disc-like aluminum alloy cutterhead is clamped at the end of motorized spindle. The Rockwell hardness indenter is fixed in the columned clamp holder and is connected with aluminum alloy cutterhead through screw threads. In the experimental speed range, in order to make the tool and the fixture in a dynamic balancing state, a clump weight is installed in the columned clamp holder symmetrically to the aluminum alloy cutterhead. Workholder is fixed on the Kistler 9257b three-component dynamometer and the latter is fixed on the machine table, linking with a computer through charge amplifier and a data acquisition card.

During experiments, the machine spindle rotates and the rotating speed is \( n \). In order to ensure that the scratch on the test specimen is only through one cutting, the relative motion between the test specimen and the tool should be reasonably controlled. The machine tool feed movement process undergoes acceleration and uniform motion stage successively. The acceleration time or deceleration time of the feed movement of the tool is 0.1 s, and the acceleration distance or deceleration distance is 5 mm. Thus, the distance between the diamond grit tip of Rockwell hardness indenter and test specimen is 5 mm after tool setting, as shown in Fig. 6. The cutting depth is set as \( h \). The machine spindle moves to a specified position at a speed of \( v_f \) and stops for holding \( \Delta t \) seconds, and then moves back to the initial point at a speed of -\( v_f \). In addition, the holding time is crucial, because if the \( \Delta t \) is too large, the frequency of exposure between the tool and the test specimen will be more than once, while, if the \( \Delta t \) is too small, the tool will not be in contact with the test specimen. Thus, \( \Delta t \) should be determined appropriately under the corresponding spindle speed, ensuring the frequency of exposure between tool and test specimen to be only once. Specially, we...
set the suitable holding time ($\Delta t$) by observing two crucial factors. The first is whether there is only one cutting force wave (one cutting force wave means one scratch). The second is whether the actual scratch length is consistent with the theoretical estimation scratch length (computed based on cutting radius and cutting depth). If both of the two factors are satisfied, the selected holding time ($\Delta t$) is effective.

In order to investigate the detailed interface profile and surface morphology, KEYENCE VK-X250 laser scanning confocal microscope (LSCM) and FEIQ45 scanning electron microscope (SEM) were used to examine the surface of the samples. The parameters of single point dicing are shown in Table 5.

### 4 Experimental results and discussions

#### 4.1 Cutting force

In order to validate this model, a comparison was made between the simulated and experimental measurements of the cutting force. The cutting forces comparison between simulation and experiment are shown in Fig. 6. Due to the SiCp/Al model in this paper is not a homogenous model, so it is difficult to estimate the precise cutting force curves. Furthermore, the cutting length and time discrepancies between simulation and experiment also lead to the difference between simulation and experiment cutting force curves. Wang [16] et al. also got the similar simulation cutting force curves of SiCp/Al composites. However, the simulation can obtain a good estimation of the value and change trends of cutting force as shown in Fig. 6 and Table 6. The maximum, minimum, and average values of cutting force were calculated from the data based on the simulation and experiment, as shown in Table 6. The average cutting force error of Al alloy and SiCp/Al is 8.67% and 8.06%, respectively. By calculating the average cutting force error of simulation and experiment, which is also used by Zhou et al. [34], can prove that simulation model is reasonable.

#### 4.2 Overall surface topography

The overall surface topography of the three materials is shown in Fig. 7. It can be seen that the scratch appearance of aluminum alloy is clear. Material accumulation appeared on both

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### Table 5 The parameters of single point dicing

| Cutting depth $h/\mu m$ | Cutting radius $r/mm$ | Cutting speed $V_s/(m/s)$ | Holding time $\Delta t/s$ | Feed speed $V_f/(mm/min)$ |
|------------------------|-----------------------|---------------------------|--------------------------|---------------------------|
| 20                     | 162                   | 5.26                      | 0.1-0.15                 | 100                       |

### Table 6 Material parameters of 2A12 Al alloy and SiCp/Al

| Cutting force      | Maximum (N) | Minimum (N) | Average (N) | Average error (%) |
|--------------------|-------------|-------------|-------------|-------------------|
| Al alloy (simulation) | 20.6244    | 2.3504      | 12.2999     | 8.67              |
| Al alloy (experiment) | 18.7298    | 0.5215      | 11.3194     |                   |
| SiCp/Al (simulation)  | 32.1861    | 1.18098     | 15.1241     | 8.06              |
| SiCp/Al (experiment)  | 23.9737    | 0.2536      | 13.9960     |                   |
sides of scratch centerline showing plastic flow features. In the case of 65% SiCp/Al composites, material accumulation also occurs on both sides of scratch centerline. However, the centerline is poor than aluminum alloy, and the accumulation of materials is discontinuous, having low surface flatness. The overall surface topography of the two materials matches the simulation well. Aluminum alloy has good plastic-flow features, and there are common phenomena in metal cutting process, such as scraping, plowing, and cutting. In the case of 65% SiCp/Al composites, although the aluminum matrix still

Fig. 7 The overall appearance of three materials after dicing

Fig. 8 The scratch profile dimensions of 2A12 Al alloy and SiCp/Al composite after dicing
has plasticity features, the addition of SiC increases the brittleness of SiCp/Al composites and causes the low surface flatness. It can be seen that the increase of volume fraction of SiC will decrease the surface quality of cutting.

Further, we can find that the scratch centerline of Vol 45% SiCp/Al is more blurred than aluminum alloy, which means the higher surface roughness and lower cutting quality. What is more, the scratch centerline of Vol 45% SiCp/Al is more clear than Vol 65% SiCp/Al and there is no obvious discontinuity as well as surface unevenness phenomena on the overall surface topography of Vol 45% SiCp/Al. Therefore, the cutting quality of Vol 45% SiCp/Al is worse than aluminum alloy, but better than Vol 65% SiCp/Al, which confirms the

### Table 7  Profile fluctuation data analysis and statistics about Fig. 8c.

| Cutting force | 2A12 Al alloy | SiCp/Al |
|---------------|---------------|---------|
| Minimum $\beta$ ($\mu$m) | -20.243 | -19.229 |
| Maximum $\gamma$ ($\mu$m) | -17.693 | -12.894 |
| Maximum fluctuation ($\gamma-\beta$) | 2.550 | 6.335 |
| Average $\alpha$ ($\mu$m) | -19.494 | -16.369 |
| Standard deviation $\sigma$ ($\mu$m) | 0.323 | 1.363 |
| Variance ($\mu$m) | 0.105 | 1.857 |
| Fluctuation range ($\alpha \pm 2\sigma$) | [-20.141, -18.847] | [-19.094, -13.643] |
simulation inference that the increase of volume fraction of SiC will decrease the surface quality of cutting.

### 4.3 Morphology of longitudinal cross-section

The scratch profile curves of the two materials were measured by confocal laser scanning microscope. The profile variation is shown in Fig. 8a. Parts “b,” “c,” and “d” marked in Fig. 8a, correspond to the cut-in parts (Fig. 8b), maximum cutting depth parts (Fig. 8c), and cut-out parts (Fig. 8d). Figure 8b, c, and d is a partially enlarged part of Fig. 8a. It can be seen that the scratch profile curve of aluminum alloy is most similar to the nominal profile curve among the two materials. The profile integrity is good and the profile fluctuation is small. However, the scratch profile curve of 65% SiCp/Al composites obviously deviates from the nominal profile curve and the range of profile variation is obviously wider than aluminum alloy. It shows that the addition of SiC increases the brittleness of SiCp/Al composites and the brittle fracture causes the remarkable profile fluctuation. Thus, the profile integrity of 65% SiCp/Al composites is worse than aluminum alloy as well.

From further analyses of cut-in parts (Fig. 8b), maximum cutting depth parts (Fig. 8c), and cut-out parts (Fig. 8d), it can be seen that, in the initial cut-in stages, the plastic deformation of aluminum alloy occurred under the action of tool, and the profile dimension is similar to the nominal profile dimension. Since the SiC increase the hardness of SiCp/Al composites, the amount of deformation in the initial stage is small and the fluctuation of deformation increases with the deepening of the tool. It can be seen that from Fig. 8, the profile fluctuation range of aluminum alloy is about 3 μm, but the profile...
fluctuation range of SiCp/Al composites, which is almost 3 times of the aluminum alloy, is about 8 μm. In maximum cutting depth parts (Fig. 8c), the profile curve of aluminum alloy is almost as same as the nominal profile curve and the profile fluctuation is very small, the profile fluctuation range reaching its minimum. However, the profile fluctuation of SiCp/Al composites is big and the profile fluctuation range reaches its maximum. The profile fluctuation data analysis and statistics about Fig. 8c is shown in Table 7. The reason for the phenomenon is that, at maximum cutting depth part, in the process of cutting, plastic deformation was mainly undergone in aluminum alloy, but brittle fractures were mainly undergone in SiCp/Al composites.

From the longitudinal section morphology of the scratch, it can be seen that the fluctuation of the profile curve of the SiCp/Al composites increases with the addition of SiC. The cutting quality of SiCp/Al composites is obviously lower than aluminum alloy, indicating that the simulated analysis matches the test well.

4.4 Scratch micromorphology

In this section, we first use the scratch micromorphology of aluminum alloy and Vol 65% SiCp/Al to validate the effectiveness of the simulation in Fig. 9. Then, in Fig. 10, we show the scratch micromorphology of all materials in maximum cutting depth to confirm the simulation inference that the increase of volume fraction of SiC will decrease the surface quality of cutting.

The results of cutting simulations are compared to single-point cutting experimental results, as shown in Fig. 9a and b. It can be seen that, except for plastic deformation, some scales were found on the surface of 2A12 Al. The reason for the generation of scales is considered that the tension stress in the cutting process may induce crack growth and so scales damage appear on the surface of the workpiece, as shown in the Fig. 9c and d. Furthermore, in cutting process of SiCp/Al composites, the scale phenomenon will induce defects like Al tearing and interface debonding.
The simulation and experimental results of SiCp/Al composites are shown in Fig. 9e-n. The phenomena of interfacial debonding and SiC cleavage can be seen from Fig. 9e and f. It is because that there can be randomly scattered original micro-cracks on the surface of SiC, being very easy to cause cracks growth under the squeezing action of the tool. This can cause a cleavage phenomenon on the surface of SiC and make the aluminum alloy matrix squeezed, causing plastic deformation in the direction of weak restrictions and concentrates stress between the interface of aluminum alloy matrix and SiC. Furthermore, when the stress exceeds the interfacial limit strength, there can be the phenomena of interfacial debonding. Furthermore, the large tensile stress will also lead to interfacial debonding, as same as the mechanism of scale phenomenon in 2A12 Al.

The phenomena of micro-cracks, SiC particle breakage, and Al-matrix tearing can be seen from Fig. 9g and h. With the interaction between the abrasive particle and material, the large tensile stress behind the abrasive particle will lead to micro-crack initiation and Al-matrix tearing. According to indentation fracture mechanics, if the normal stress in the contact-position of SiC exceeds the fracture strength, it will cause median and lateral cracks. With the movement of abrasive particle, the horizontal crack extends to the surface and causes the breakage of SiC.

The phenomena of SiC protruding and pulling out can be seen from Fig. 9i and j. With the movement of abrasive particle, if the interfacial strength of the upper half of the SiC much larger than the bottom half one, it will cause SiC pulling out and lead to pits on the surface. Furthermore, if the pulling out SiC is pressed into the Al matrix by abrasive particle again, it may cause protruding of SiC. In addition, when the tensile stress is very large, the serious interface debonding will cause the protruding of SiC under the Al matrix as well, as shown in Fig. 9i.

The phenomenon of Al-matrix covering can be seen in Fig. 9k and l. That is because the extrusion of Al-matrix between the SiC produces secondary shear deformation under the action of abrasive particles being very easy to cover the SiC in the direction of cutting. From Fig. 9l, it can be seen that the phenomenon of Al-matrix covering is especially serious and this is because the high volume fraction of SiC makes the deformation of the Al-matrix be hindered and the excessive shear stress makes the phenomenon of Al-matrix tearing be more serious. There are many pits and cracks in the cladding, as shown in Fig. 9m, causing the weak bonding strength and making the SiC easy to break off. After cleaning the SiCp/Al composites with ultrasonic washer for 10 min, most of the surface claddings shown in Fig. 9n are cleared, showing the broken particles and cladding fracture surface, as shown in Fig. 9m and l. Thus, it can be seen that the cladding formed by plastic deformation of Al-matrix in the cutting of SiCp/Al composites process is also an important defect influencing the surface quality.

The different positions tagged in the Fig. 9n are analyzed by energy-dispersive spectroscopy (EDS) and the major elements are identified, as shown in Fig. 10. It can be seen that the main elements of position tagged number 1 is Al. The position tagged number 2 has the highest amount of Al and the next is silicon. The major elements of position tagged number 3 and 4 are silicon. Thus, the energy spectrum analysis results show that bellowing the cladding is broken SiC and the cladding consists of Al-matrix and clastic SiC, verifying the inference of preceding part of the text.

SiC brittle fracture is one of the important factors to cause the bad surface quality. From Fig. 9 we can know that the broken SiC will lead to pit defects, interface debonding and Al matrix tearing and finally the surface quality is bad. The lower SiC volume fraction results in good plasticity of Vol 45% SiCp/Al than Vol 65% SiCp/Al and relieves the brittle fracture phenomenon in cutting process. Therefore, from Fig. 11, Scratch micromorphology of three materials in maximum cutting depth
11, we can find that the cutting quality of aluminum alloy is best and Vol 65% SiCp/Al is worst. Vol 65% SiCp/Al has higher brittleness, which leads to the bad surface flatness once the SiC crushes. However, due to the lower SiC volume fraction, there are fewer SiC brittle fracture phenomenon and so the Vol 45% SiCp/Al has a better surface flatness and cutting quality than Vol 65% SiCp/Al.

5 Conclusions

In this paper, the single-point cutting simulations and experiments were conducted for high-volume fraction SiCp/Al composites and Al alloy. The surface topography was observed, and the surface formation characteristics of 65% SiCp/Al composites were analyzed. Good agreement was found between the experimental and simulation results. The following conclusions can be drawn:

1) The removal characteristics of SiCp/Al composites are different from the Al alloy materials. In the cutting process of SiCp/Al composites, there are plastic deformation, plowing, and cumulating of Al alloy, and slippage, detachment and crushing of SiC.

2) The high-volume SiC increase the brittleness and cause the defects like interfacial debonding, al tearing, protruding, and pulling out, crushing, part crushing, and so on. These defects make the profile fluctuate widely. Thus, it lowers the surface quality and profile dimensional accuracy of SiCp/Al composites.

3) With the cutting depth increases, fluctuations of SiCp/Al profile becoming larger. The range is zero to 8 μm when the cutting depth increased gradually to 20 μm.

4) There are thin and discrete layers covered on the machined surface. The layers consist of Al-matrix and clastic SiC.

Nomenclature

σ, flow stress (Mpa); A, yield stress at reference temperature and strain rate (Mpa); B, strain hardening coefficient (Mpa); ε, plastic strain; n, the strain hardening exponent; m, thermal softening exponent; ε, strain rate; εf, reference plastic strain rate; T, workpiece temperature(K); Tm, material melting temperature(K); Toom, room temperature(K); dldξ, Failure parameters of matrix materials; wξ, scalar of failure state; Δεf, equivalent plastic strain during each integration cycle; μ, coefficient of sliding friction; ρ (εεf), shear retention factor of material; p, material parameters; εf, fracture strain; η, stress triaxiality; p, pressure stress (Mpa); q, von Mises equivalent stress (Mpa); εp, plastic strain rate; εr, reference strain rate; Tt, transition temperature defined as the one at or below which there is no temperature dependence on the expression of the fracture strain (K); σ1, σ2, σ3, principal stresses in three directions respectively (Mpa); σem, tensile strength of material (Mpa); τ, friction force(N); P, positive pressure (Mpa); σ0, tensile strength of material; μh, normal displacement at failure; Gf, mode I fracture energy; σG, shear modulus after the crack opening; G, shear modulus of the undamaged material; εc, cracking opening strain; ε, material parameters

Availability of data and material The authors confirm that the data and material supporting the findings of this study are available within the article.

Code availability Not applicable.

Author contributions Yong-jie Bao provides the support of research project. Yong-jie Bao, Shou-xiang Lu, and Hong-zhe Zhang developed the conceptual framework and research protocol for the study. Xu-Zhang completed the simulation analysis task. Shou-xiang Lu completed the task of single-point cutting test. Yong-jie Bao, Shou-xiang Lu, and Hong-zhe Zhang conducted the publication review and offered writing instructions. Xu Zhang drafted the manuscript and made major revisions. All authors approved the final version of the manuscript.

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Declarations

Ethics approval Not applicable.

Consent to participate All authors have checked the manuscript and approved to submit to your journal.

Consent for publication We would like to submit our original research article entitled “Investigation on the removal characteristics of single-point cutting high-volume fraction SiCp/Al composites” to your journal named “The International Journal of Advanced Manufacturing Technology”. Neither the entire paper nor any part of its content has been published or has been accepted elsewhere. It is not being submitted to any other journal simultaneously.

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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