Study on the edge defects of high volume fraction 70% SiCp/Al composites in ultrasonic-assisted milling

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Abstract
Directing at the hard machinability of high volume fraction 70% SiCp/Al composites, a longitudinal and torsional ultrasonic-assisted milling (LTUAM) method is proposed to improve the edge quality and machining efficiency. By observing the metallographic structure of the material, a three-dimensional (3D) finite element model of random distribution of spherical, elliptical and polygonal SiC particles is established and analyzed by ABAQUS simulation software. The formation mechanism of edge defects, stress distribution, defect characteristics and the effect of machining parameters on milling forces are investigated during ultrasonic-assisted milling. The results show that the edge defects appear at the inlet, outlet and middle edge position, especially is more serious at the outlet position. The SiC particles failure modes mainly include particle pull-out, particle shearing, and crushing, moreover, the edge defects mainly include matrix tearing, edge breakage, burrs, bulges and pits. Ultrasonic-assisted milling (UAM) with a certain range of ultrasonic amplitude could effectively reduce the surface fragmentation rate and milling force, and it not only could slow down the expansion of cracks, but also increase the plastic flow of material, and obtain better edge quality compared with the traditional machining method. Comparing the results of finite element analysis and experimental tests, it shows that the simulation results are in good agreement with that of tests.

Keywords 70% SiCp/Al composites · 3D finite element analysis · Edge defects · LTUAM · Milling force

1 Introduction

SiCp/Al composites own excellent properties such as high specific strength, specific stiffness, specific modulus, good wear resistance and low heat expansion coefficient, so they are widely used in military, aerospace and electronic packaging [1–4]. However, it is difficult to machine due to the high brittleness and low toughness. SiCp/Al composites machined by traditional machining methods always have poor surface quality and edge defects such as spalling, edge collapse, burr and fragmentation, and the processing is inefficient. Especially, the edge defects are easy to appear at the end of the workpiece [5, 6]. These irreparable defects seriously affect the accuracy of the workpiece, which greatly increases the processing cost [7]. Therefore, how to obtain high-quality surface and reduce edge defects for high volume fraction SiCp/Al composites is a crucial issue to be solved during machining.

Aiming at the problem of traditional processing, some non-traditional machining methods were used to improve the edge quality of particle reinforced composites and other difficult machining materials by scholars, such as laser machining and ultrasonic-assisted machining. Laser-assisted machining (LAM) is a process that could soften the matrix material by laser heating and then improve the cutting performance. Many studies have shown that it can improve the edge quality and reduce the cutting force. Yang et al. [8] conducted laser-assisted milling experiments on silicon nitride ceramics and found that the edge defects at the exit were significantly reduced when the temperature exceeded 1000 °C. Woo [9] conducted a study for silicon nitride materials and found that the cutting force decreased, and the size of edge defect was improved with the increase of temperature. He also pointed out that laser-assisted turning machining has been widely used, but laser-assisted milling is still in the exploration stage due to many difficult problems such as the control of laser heat source and tool path, and equipment development. Ultrasonic-assisted machining is a machining method that periodic ultrasonic
vibration is applied to the tool or workpiece, which could make the tool and workpiece produce periodic separation. It is more commonly used in hard and brittle materials and other difficult machining materials. Chen et al. [10, 11] explored the fracture mechanism of Cf/SiC composites and pointed out that ultrasonic-assisted grinding effectively reduced the maximum undeformed chip thickness and improved the surface quality. Wang et al. [12] studied the mechanism of the size reduction of edge damage at the exit of the hole during rotary ultrasonic-assisted drilling of quartz glass and found that the reduction of crack size and cutting force are important factors for the reduction of edge size. Juri et al. [13] summarized the current stage of processing characteristics of fiber-reinforced silicon carbide ceramic matrix composites, and pointed out that ultrasonic-assisted processing can effectively reduce edge defects. The results showed that ultrasonic-assisted processing can effectively improve the quality of the edges and the equipment is easy to control, but the formation mechanism of edges defects of SiCp/Al composites in ultrasonic-assisted processing has not been investigated.

From the above literature, lots of researches have been done in experimental processing for the formation mechanism of edge defects, but the cutting mechanism of inhomogeneity material is more complex and it can’t be fully revealed only through experiments. So the finite element simulation has also been a hot spot which explore the damage mechanism. Fang et al. [14] developed a 2D milling force model and investigated the relationship between burr size and milling force and learned that the change of milling force was consistent with the change of burr size, and UAM effectively reduced the burr height. Yadav et al. [15] conducted a 2D finite element simulation and experimental research on Ti6Al4V material and predicted the burr height by the simulation. Yu et al. [16] established a 2D polygon particle model with a random distribution of SiCp/Al. Then he analyzed the formation mechanism of turning surface defects and the damage behavior of particles. Zhou et al. [17] conducted two-dimensional orthogonal finite element simulation and experiments, and discovered that the fracture surface at the exit was very rough and the SiC particles occurred brittle fracture. Niu et al. [18] established a 3D model to investigate the relationship between the tool radius and edge defects, but he ignores the effect of particles. Table 1 summarizes the simulation model during machining and the differences between this paper. From the above studies, it can be seen that there are more researches on the burrs phenomenon in plastic materials, or 2D heterogeneous mode of polygonal particles and 3D homogeneous mode of SiCp/Al composite in TM processing, while there are little pieces of research on 3D homogeneous model of polyhedral particles in UAM.

Since SiCp/Al composites are composed of SiC particles and aluminum matrix, the interaction between them and the fracture of SiC particles should be considered. In this paper, for the practical need of machining process and finding a better way to control edge defects, a 3D finite element model was built with enhanced phase shape of sphere, ellipsoid, and random polyhedron by ABAQUS simulation software. The edge defects forming process and the effect of machining parameters on milling force for 70% SiCp/Al composite material during LTUAM were investigated through finite element analysis. Finally, the simulation results were compared with the experimental results, which provided a theoretical basis for more effective machining. Figure 1 is the flow chart of this chapter.

Table 1  simulation model and processing method

| Author            | Model | Material type                  | Method | Content       |
|-------------------|-------|--------------------------------|--------|---------------|
| Fang et al. [14]  | 2D    | Homogeneous                    | UAM    | burrs         |
| Yadav et al. [15] | 2D    | homogeneous                    | TM     | burrs         |
| Yu et al. [16]    | 2D    | polygonal particles            | TM     | subsurface defects |
| Zhou et al. [17]  | 2D    | polygonal particles            | TM     | Edge defects  |
| Niu et al. [18]   | 3D    | homogeneous                    | TM     | Edge defects  |
| This article      | 3D    | sphere, ellipsoid, polyhedron  | LTUAM  | Edge defects  |

Fig. 1  Flow chart
2 Finite element simulation of LTUAM

2.1 Mechanism of LTUAM

Ultrasonic vibration cutting refers to applying ultrasonic vibration based on traditional machining. Periodic vibration is usually applied to the tool or workpiece to meet the needs of ultra-precision machining. However, no matter what direction of vibration is applied, it can be seen as a simple harmonic motion on the tool. Longitudinal and torsional composite ultrasonic vibration-assisted milling is based on longitudinal ultrasonic vibration applied with the same frequency of circumferential torsional vibration. Figure 2 is a schematic diagram of longitudinal torsion ultrasonic-assisted milling.

As follows, according to the traditional milling cutting edge motion trajectory equation, the trajectory equation is obtained by applying longitudinal and torsional ultrasonic vibration in Eq. (1):

\[
\begin{align*}
  x(t) &= r \cdot \sin(2\pi nt/60 + A_2 \cdot \sin(2\pi ft + \varphi_2)/r) \\
  y(t) &= v_f \cdot t + r \cdot \cos(2\pi nt/60 + A_2 \cdot \sin(2\pi ft + \varphi_2)/r) \\
  z(t) &= A_1 \cdot \sin(2\pi ft + \varphi_1)
\end{align*}
\]

(1)

In the formula, \(v_f\) is the feed speed of the milling cutter, \(r\) is the radius of the cutter, \(n\) is the speed of the milling cutter, \(f\) is the frequency of the ultrasonic vibration, and \(A_1, \varphi_1\) are, respectively, the amplitude and initial phase of the longitudinal ultrasonic vibration, and \(A_2, \varphi_2\) are, respectively, the amplitude and initial phase of the torsional ultrasonic vibration.

As shown in Fig. 3, the cutter of longitudinal and torsional vibrations periodically separated from the workpiece, which is conducive to chip outflow and reducing the extrusion of the flank face on the machined surface. Therefore, it can effectively reduce the cutting force and improve the machining quality.

2.2 Equivalent cutting width

Since the trajectory of any point on the tool is a helix which that changes according to the sinusoidal law during LTUAM, the simulation model is too complex and difficult to calculate if using the actual shape and size of the tool and workpiece. Therefore, the simulation model of LTUAM is simplified, and the study is carried out with the teeth of one milling cutter as shown in Fig. 4.
The chip Angle is:

\[ \theta = \pi - \cos^{-1} \left( \frac{f_d}{2r} \right) \]  

(2)

The cross-sectional area of the equivalent chip is:

\[ S = \frac{1}{2} r^2 \left[ \pi - 2 \cos^{-1} \left( \frac{f_d}{2r} \right) + \sin \left( 2 \cos^{-1} \left( \frac{f_d}{2r} \right) \right) \right] \]  

(3)

The equivalent milling width is:

\[ h = r - r \sqrt{\frac{\cos^{-1} \left( \frac{f_d}{2r} \right) - \sin \left( 2 \cos^{-1} \left( \frac{f_d}{2r} \right) \right)}{\pi - \cos^{-1} \left( \frac{f_d}{2r} \right)}} \]  

(4)

where \( S \) is the cutting layer formed by two feeds, \( r \) is the milling radius, and \( H \) is the equivalent cutting width \( f_d \) is the milling width.

### 2.3 Finite element analysis parameters and equivalent milling width model

Figure 5 shows the microstructure of high volume fraction 70% SiCp/Al composite with the size of 20 × 15 × 10mm³. By comparing the shape and distribution of SiC particles in the metallographic photos of SiCp/Al composite, the model of SiC particles shown in Fig. 6 is established for reflecting the actual machining process and the stress change. The volume of reinforced SiC particles accounts for 70% of the composite, and the average diameter is 45 μm. The SiC particles are randomly distributed in the aluminum matrix material, and the reinforced phase can be penetrated. Meanwhile, the boundary conditions are defined as periodic boundary conditions. Figure 6 shows a model of the 3D milling process, where the main shapes of the model reinforcing phase SiC are 24-sided, 12-sided, spherical, and ellipsoidal. As the milling cutter selected is an end milling cutter, Fig. 7 is the equivalent right-angle cutting model, and the point P is the application point of amplitude application.

### 2.4 Boundary conditions and element types

In the finite element model, all the degrees of freedom on the workpiece are restricted. By setting the PCD tool as a rigid body and establishing a reference point on the tool to apply velocity and ultrasonic vibration, the calculation time can be reduced. Since the hardness of the PCD tool is 8000HV, which is higher than the stiffness of the SiCp/Al composite, the effect between the chip and the tool can be
The aluminum matrix, SiC particles and the tool all adopt the C3D8RT element attribute. The aluminum matrix and SiC reinforced phase are assembled for tie binding to simulate the interfacial phase. The workpiece is made of hexahedron and divided into two parts, and the mesh of the chip layer is refined, which can not only save time but also improve the accuracy of the simulation results.

**2.5 Constitutive equation**

In this paper, the aluminum alloy 6061 is used as aluminum-based material. Considering the high strain rate, high temperature and high strain during high-speed ultrasonic-assisted milling. The constitutive model proposed by Nasr et al. [19] is adopted in the calculation, and its formula is shown in Eq. (2).

\[
s_y = (A + BE^N) \times \left(1 + C \ln \dot{E}^N\right)(1 - T^*(M))(1 + CV_d \ln \dot{E}^N)
\]

\[
\dot{E}^N = \frac{\dot{E}}{\varepsilon^0}
\]

\[
T^* = \frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}}
\]

\[
g = 1 + a(V_d) + b(V_d)^2 + c(V_d)^3
\]

where \(\sigma\) is the yield stress, \(\varepsilon^0\) is the reference strain rate. \(A\) is the initial yield stress, \(B\) is the stress hardening constant, \(N\) is the stress hardening index, \(M\) is the strain rate constant, \(C\) is the softening index, \(V_d\) represents the volume fraction of particles with an average diameter \(T^*\) is the specific temperature, \(\dot{E}^N\) is the effective plastic strain, \(T_{\text{room}}\) is the room temperature, \(T\) is the specimen temperature, \(T_{\text{melt}}\) is the melting temperature.
The fracture strain of the material proposed by Ghandehariun et al. [20] should be considered in the cutting process:

\[ e^f = \max \left\{ D_1 + D_2 \exp(D_5 \sigma^*) \left[ 1 + D_4 \ln \dot{\varepsilon}^* \right] \left[ 1 + D_3 T^* \right], EFMIN \right\} \]  

(9)

where \( \sigma^* \) is the ratio of pressure to effective stress, \( D_1 \sim D_5 \) is the fracture constant, \( EFMIN \) is the lower limit value of fracture strain calculation, \( \Delta \varepsilon^p \) is the effective plastic strain increment. It will lead to fracture and chip separation of materials when the damage variable \( D \) reaches 1. The Damage parameter \( D \) is in Eq. (6), and \( \Delta \varepsilon^p \) is the increment of effective plastic strain.

\[ D = \left( \sum \Delta \varepsilon^p \right) / e^f \]  

(10)

Table 2 shows that the material constants of the constitutive model for aluminum alloy matrix, and Table 3 shows the damage parameters, Table 4 shows the material performance parameters, and Table 5 shows the milling parameters.

### 3 Experiment procedures

The validity of the finite element model is verified through experiments. Fig. 8 shows the experiment setup. The entire test process of longitudinal and torsion ultrasonic-assisted milling of SiCp/Al composite material is completed on a VMC850E three-axis vertical machining center. The PCD tool is used to mill SiCp/Al composite materials and the experimental parameters are consistent with the simulation parameters. The device of force measuring is a Kistler 9257B triaxial dynamometer. The microscopic morphology of the edge defects is observed by scanning electron microscopy.

### 4 Results and analysis

#### 4.1 Formation mechanism and stress distribution of edge defects during machining

Figure 9 shows the stress change of the workpiece in an ultrasonic vibration cycle at the inlet during the process of ultrasonic-assisted milling. In the milling process, the machining parameters are the milling depth of 0.5 mm, the feed rate is 0.007 mm/Z, the milling speed is 135 m/min, the ultrasonic longitudinal amplitude is 2.5 um and corresponding torsional amplitude is 1.7 um. The stress decreases first and then increases, which indicate that there is a cutting-separation-recutting cycle process between the tool and the workpiece. When the material is subjected to squeezing and shearing by the cutter, plastic deformation occurs in the aluminum matrix. And the maximum stress exceeds the yield stress, so the shear slip zone begins to form. The matrix drives the SiC particles forward which makes the stress around SiC particles change. The SiC particles are also prone to elastic deformation due to the contact with the tool, which will lead to cracks at the bonding surface. The cracks of SiC particles are prone to matrix tearing and accompanied by burrs. Figure 10 shows the fracture situation of SiC particles at the entrance of aluminum matrix removal. The contact between the rake face and SiC particles leads to a sharp increase in the force on the particle tip until the brittle fracture criterion is reached, and the particles are broken and cut. Different degrees of fracture are formed at the entrance as the heterogeneity of the material. Partially broken particles leak out of the surface of the workpiece, which is further squeezed and rubbed by the flank face of the tool, resulting in stress concentration at the tip of the particles. At the same time, the stress increases between particles under the squeezing action, resulting in a stress concentration at the contact position. When the principal stress is larger than the fracture strength of SiC particles, the SiC particles will be broken and lead to
The yield strength of the material under the squeeze of the stress around the particles is the largest and exceeds the lower left and front lower positions of the milling tool. The maximum stress is concentrated at the exit edge location of the workpiece. The maximum stress is concentrated together at an ultrasonic vibration cycle at the exit edge location of the material.

Surface bulges or debris. At the same time, some are further broken and eventually form pits or holes of different sizes. At the entrance corners, the flank face of the tool produces a shearing and squeezing friction against the SiC particles. Due to the lack of support at the edges and the different degree of deformation between SiC particles and aluminum matrix, which leads to deformation at the edges by deviating from the vertical direction. Figure 11 shows the morphology of the edge defects at the inlet.

Figure 12 shows the stress change of the workpiece in an ultrasonic vibration cycle on the middle edge location of the workpiece. The stress decreases first and then increases, and the shear zone undergoes plastic deformation and continues to extend forward, which is combined with the plastic zone. The two stresses concentrate together under shear and extrusion by the rake face, resulting in matrix tearing of the substrate. Figure 13 shows that some of the particles are separated and broken in the form of chips, and some of the particles are exposed, which are cut by the rake face or squeezed and rolled by the flank face as shown in, leading to particle crushing and material failure around the particles. Then it forms pits and bulges of different sizes. Figure 14 shows the morphology of the edge defects on the middle edge of the material.

Figure 15 shows the stress change of the workpiece in an ultrasonic vibration cycle at the exit edge location of the workpiece. The maximum stress is concentrated together at the lower left and front lower positions of the milling tool, which deviates from the milling position of the milling tool. The stress around the particles is the largest and exceeded the yield strength of the material under the squeeze of the flank face. Figure 15c shows that the bonding surface between the matrix interface and the SiC reinforcement particles produce slipping deformation. The workpiece lacks a support position, so it can no longer withstand the stress and the material breaks at the exit. Figure 16 hides off the aluminum substrate. The maximum stress is concentrated between the particles, and there is extrusion crushing between the particles, which leads to the failure of the materials surrounding the particles and finally debonding. The whole grain appears to be peeled off at the edge, forming a wide range of fractures with a large fracture depth and some chips left on the surface of the workpiece. As shown in Fig. 17, an obvious separation interface is formed. Due to the random distribution of particles, the stress at the outlet is different, which leads to different sizes of pits.

The edge defects appeared at the inlet, outlet and middle edge, and were more serious at the outlet. The particle failure modes mainly include particle pullout, particle shearing, crushing, and the edge defects mainly include matrix tearing, chipping, burrs, bumps, pits, etc.

### 4.2 Milled surface topography

To verify the simulation results and compare the difference between LTUAM and TM on the formation of edge defects, the ultrasonic longitudinal amplitude is selected as 2.5um, the torsional amplitude is selected as 1.7um, the milling depth is 0.5 mm, the feed rate is 0.007 mm/Z, the milling speed is 135 m/min and. The machined workpieces are observed by scanning electron microscope (SEM). Figure 18 shows the morphology of ultrasonic-assisted machining and ordinary machining morphology at the inlet edges and tips, respectively. There are matrix tears, cracks, small cracks and pits at the inlet. However, the entrance of ultrasonic-assisted milling is relatively flat, and the damage size is smaller than ordinary milling. In addition to these characteristics, the form of the material breakage is mainly the toughness breakage and the size of the SiC particles broken is mainly the small particles at the fracture location. But a phenomenon of over-cutting at the top corners has appeared in ordinary machining, which causes large pieces of the top to fall off. At the same time, there are burrs, particle pressing, large crack, overall particle pulling out and overall particle shearing appeared, resulting in the edge defects at the inlet. As the tool intermittently contacts the workpiece at a high frequency during LTUAM machining.

**Table 5** Cutting parameters used in milling experiments

| Parameter             | Numerical value |
|-----------------------|-----------------|
| Vertical amplitude(um)| 0, 1.5, 2.5, 3.5, 4.5 |
| Torsion amplitude(um) | 0.1, 1.7, 2.3, 3.1 |
| Milling speed(m/min)  | 45, 75, 105, 135, 165 |
| Feed rate(mm/z)       | 0.007, 0.009, 0.011, 0.013, 0.015 |
| Depth of cut(mm)      | 0.1·0.3·0.5·0.7·0.9 |
| PCD tool parameters   | Rake angle 5°, Tool clearance 10°, Teeth Z = 2, Cutter diameter D = 8 mm |

**Fig. 9** Stress in an ultrasonic vibration period: (a) contact step; (b) separation step; (c) larger magnification for separation step; (d) recontact step
the shear angle could be increased and the material deformation degree could be reduced. Therefore, the impact force of the tool on the workpiece would reduce. It is proved that UAM can restrain the appearance of burrs and cracks and improve the quality of the entrance compared with traditional processing.

Figure 19 shows the micro-morphology of middle position in UAM and TM respectively, both of which form pits of different sizes. The edge is flatter and the material removal method is mainly plastic removal in ultrasonic-assisted milling. However, it has large plastic bumps and pits caused by large particle fractures in ordinary milling, accompanied by burrs and large cracks. This is due to the high temperature during the machining process and the large thermal deformation caused by ordinary milling. But the friction and the cutting temperature between tool and workpiece are reduced as the high-frequency vibration of ultrasonic-assisted milling. So it reduces the plastic deformation and enhances the plastic flow, which improves the ductility of the material and reduces the large gap caused by the debonding of matrix and particles.

Figure 20 shows the micro-morphology of outlet position in UAM and TM, respectively, whatever form of edge fracture, the fracture depth of TM is larger and accompanied by debris and burrs. Since ultrasonic milling produces a large number of tiny cracks and powdering under high-frequency hammering, the force become small of removing material and reduces the edge defects at the exit.

The test results show that the edge defects mainly appear in the inlet, middle edge and outlet positions, and the fracture at the outlet position is the most serious. The inlet location mainly includes pits, holes, matrix tearing, and the middle edge location mainly includes pits, bulges. The outlet location contains large fracture edge collapse. The results of edge defects appearing in the experiment are consistent with the simulation results. Compared with ordinary cutting, the method of ultrasonic-assisted milling could suppress the generation of burrs and cracks, and the material removal way is mainly plastic removal mode, which improves the quality of the edges. Therefore, it is necessary to study the effect of different ultrasonic machining parameters on the edge defects.

4.3 Influence of machining parameters on cutting force

Since the cutting force is an important factor affecting the deformation and damage of the workpiece, this section explores the effect of machining parameters on the milling force, which indirectly responds to the degree of edge defect breakage and provides a basis for reducing edge defects. Figure 21 shows that the comparison between the simulation and experiment values of axial force for TM and LTUAM with different machining parameters. It is founded that the cutting force increases with the increase of feed rate and depth of cut. With the increase of feed rate and depth of cut, the material removal rate and the chance of interaction between the tool and SiC increase, so the force of tool against material deformation and friction will increase. The cutting force first increases and then decreases with the increase of cutting speed. It is easy to produce a plastic tumor when the speed is small, so the forces increase. But the cutting force decreases with the cutting speed continues to increase. As the heat generates in the shear zone within a short period time and cannot be transferred to the chip interior in time, so the temperature of the shear zone increases. Therefore, the workpiece undergoes a certain degree of softening, which reduces the contact time between the rake face and the chip and makes the acting time of frictional force decrease. The cutting force first decreases and then increases as the amplitude increases. Because the periodic contact and separation between the cutting edge and the workpiece improves the heat dissipation conditions in the cutting area when the right amplitude is applied. It will reduce the squeezing pressure and friction between the tool and the chip and promote the sprouting and expansion of microcracks. If the amplitude is too large, it will cause the tool vibrate strongly. Wu et al. [21] pointed that the mechanism may vibrate with the frequency of the excitation source when the frequency of the excitation source changes.
Fig. 12 Stress in an ultrasonic vibration period: (a) contact step; (b) separation step; (c) recontact step

Fig. 13 Particle breakage changes in the middle position: (a) particles are sheared; (b) the particles are crushed (c) the cutting is complete

Fig. 14 Defect of middle edge: (a) intermediate position topography (b) large amplification for Intermediate position topography

Fig. 15 Stress in an ultrasonic vibration period: (a) contact step; (b) separation step; (c) recontact step
near a certain resonance frequency. It will enhance the interaction force between the tool and SiC particles, resulting in the chance of particle pulling out and crushing, so the cutting force increases. Moreover, the simulation value is less than the experiment, because the tool is set as a rigid body in the simulation process and the tool wear is not considered. In addition, it is also affected by the experimental conditions. Such as the cutting force is one cause of the vibration of the machine tool in the milling process [22, 23], in turn, it will affect the cutting force. The error range between the experiment value and the simulation value is within 18%, so the simulation analysis can predict the force change in the actual machining process. To improve the quality of the edge, it is better to choose a small depth of cut and feed rate, choose a large cutting speed and appropriate ultrasonic amplitude in the actual machining process.

Fig. 16 Particle breakage changes at the outlet: (a) particles are sheared; (b) Particle detachment (c) extrusion friction (d) the cutting is complete

Fig. 17 Defect of middle edge: (a) outlet topography

Fig. 18 Microstructure at the inlet: (a) LTUAM, (b) LTUAM, (c) large amplification for (b), (d) TM, (e) TM (d) large amplification for (e)
Fig. 19  Microstructure at the middle edge: (a) LTUAM, (b) large amplification for (a), (c) TM, (d) large amplification for (c)

Fig. 20  Microstructure at the outlet: (a) LTUAM, (b) large amplification for (a), (c) TM, (d) large amplification for (c)
Fig. 21  Effects of machining parameters on milling forces: (a) Feed rate; (b) Depth of cut; (c) Cutting speed; (d) Longitudinal amplitude (e) Depth of cut
5 Conclusions

A 3D finite element model of SiCp/Al composite with 70% volume fraction was established by ABAQUS simulation software, which used to investigate the formation mechanism of edge defects, stress distribution, defect characteristics and the effect of ultrasonic machining parameters on the milling force during UAM. Compared with the experimental results, these results agree well and the following conclusions are obtained.

1. Edge defects are found at the inlet, middle edge and outlet positions and the most severely broken is at the outlet position. The inlet location mainly includes pits, holes, matrix tearing, and the middle edge location mainly includes pits, bulges and other defects. These two positions are mainly sheared and squeezed by the tool, resulting in particle shearing, breaking, crushing, pulling, etc. The outlet location contains large fracture edge collapse and ductile behavior accompanied by burrs, debris and so on. It is mainly due to the stress concentration as it lacks support at the outlet location.

2. By observing the microscopic morphology of the edge defects, the method of ultrasonic-assisted milling can effectively reduce the breakage size so that get a flatter surface and the broken SiC particles are mainly small particles compared to the traditional machining. As it enhances the plastic flow of the material and suppresses the length of burrs and cracks. While the main failure process of traditional machining is mainly brittle fracture and the broken SiC particles are mainly large particles.

3. In a certain range of ultrasonic amplitude, ultrasonic-assisted milling can effectively reduce the milling force. The cutting force increases with the increase of cutting depth and feed rate, and the cutting force first increases and then decreases with the increase of cutting speed. Therefore, choosing small milling depth and feed rate, high milling speed and appropriate amplitude can effectively inhibit the edge defects during machining.

Declarations

Ethical approval I would like to declare on behalf of my co-authors that the work described was an application that has not been published previously, and not under consideration for publication elsewhere, in whole or in part.

Consent to participate All authors know and agree to be co-authors.

Consent to publish All authors agreed to be published.

Conflict of interest The authors have declared that there are no conflicts of interest.

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