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ORIGINAL ARTICLE

Study on characteristics in high-speed milling SiCp/Al composites with small particles and high volume fraction by adopting PCD cutters with different grain sizes

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Abstract

Silicon carbide particle–reinforced aluminum matrix (SiCp/Al) composites were milled at a high speed by adopting polycrystalline diamond (PCD) tools, which the diamond grain sizes were 5, 10, 25, and 32 μm. The machined materials were SiCp/Al composites which the volume fraction was 45% and grain size of SiC particles was 5 μm. The tool wear resistance and wear morphology of polycrystalline diamond cutters were investigated. And it centered on the effects of diamond grain sizes on the cutting forces as well as the machined surface roughness. The obtained results indicated the difference of corresponding tool wear resistance between larger SiC particles and smaller SiC particles during high-speed milling SiCp/Al composites with higher volume fraction. When the grain size and volume fraction of SiC granules are 5 μm and 45%, the tool wear resistances of four diamond grain sizes were all far higher than those of tools in machining composites with higher volume fraction (56%) and larger 60-μm SiC particles. And the PCD tools of larger diamond grain size acted on better wear resistance. Both the corresponding cutting forces and surface roughness were also smaller. As cutting distance increased, the variation law of cutting forces had a good correspondence with the tool wear of PCD cutters of different diamond grain sizes. The machined surface roughness had a decreasing trend in general, but the fluctuation range was tiny. The main wear morphology was flank wear and slight wear groove marks. And there was no chipping of cutting edge and coarse wear groove marks. A large amount of the machined materials was adhered on flake face in the cutting process, but built-up edge was not formed.

Keywords SiCp/Al composites · High-speed milling · Tool wear · Cutting characteristics

1 Introduction

Higher volume fraction silicon carbide aluminum matrix composite materials exhibit excellent material properties and performance, combining the advantages of metal and ceramic materials [1–4]. So SiCp/Al composites show good development prospects in aerospace, electronic packaging, precision instrumentation, automotive industry, and other fields [5–9]. The processing precision and surface finish are required to be higher for the optical grade SiCp/Al composites. However, due to containing a great deal of brittle and higher hardness SiC particles, choosing the appropriate tool material and reducing the degree of tool wear are critical for improving the machining precision and machined surface quality. Similarly, it has strong industrial practical value and significance.

Recently, milling and turning SiCp/Al composites attract more and more attentions. In the aspect of milling, He et al. [10–12] studied the tool wear, surface quality, and relevant influence factors when PCD tools were applied in the process of precision milling silicon carbide particle–reinforced aluminum matrix composites. The volume fraction was 65%, and the SiC grain size was 60~80 μm. Yang [13] focused on the effects of diamond grain sizes and cutting amounts on tool wear and surface roughness. They found that during machining SiCp/Al composites with SiC particle size of 80~120 μm, PCD cutters with 2~30-μm grain size could obtain better

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surface quality, but the tool wear was the most serious. During high-speed milling experiment in dry cutting condition when volume fraction was as high as 65% and small SiC grain size was 10 μm, Wang et al. [14] observed the effects of diamond grain sizes and milling parameters on tool wear. They pointed out that the PCD tool demonstrated the best wear resistance when diamond grain size was 10 μm. Huang et al. [15, 16] made a comparative study of the tool wear states of different tool materials for cutting SiCp/Al composite materials. It was found that PCD cutters showed better cutting performances than other tool materials. And their team further compared the advantages and disadvantages of PCD cutters with four different diamond granule sizes when SiCp/Al (56 vol.%) composites were machined at a high speed. They found that the tool wear resistance with smaller diamond granules was better. And the corresponding cutting forces and the machined surface roughness were still smaller [17].

In terms of turning, from theoretical and experimental aspects, Ge et al. [18] carried out the comparative studies on the wear morphology and cutting performance of three different types of cutting tools when SiCp/2009Al with small reinforcement SiC granules and lower volume fraction (15 vol.%) were machined in ultra-precision turning under wet cutting condition. Within the cutting distance of 6 km, PCD tools exhibited stable and perfect cutting performance, and they could obtain a lower surface roughness. The main wear forms of PCD cutters were adhesive wear pattern on flake face and abrasive wear pattern on rake face. Quan et al. [19] adopted PCD tools, cubic nitride boron CBN, TiN-coated tool, high-speed steel, and carbide tool, respectively, during turning SiC/A356 composite materials with 15% volume fraction and 2-, 14-, 42-, and 85-μm particle size. The conclusions pointed that the tool life was mainly affected by the volume fraction and grain size of SiC particles. The higher volume fraction or the larger particle size was, the shorter the tool life was. For SiC/A356 composites, traditional cutting tools were only suitable for machining finer grain size. It was necessary to choose PCD and CBN tools with higher hardness during cutting larger particle size. Ding et al. [20] focused on Al-SiC composite materials with SiC grain size of 12.8 μm and volume fractions of 20% in the process of turning. When using PCD tools and PCBN tools with different types, they found that PCD tools showed better cutting performance and higher wear resistance. There was less adhesion of machined materials on the tools. But the use of cutting fluid could not reduce the tool wear or improve the surface finish. Dyzia [21] studied the maximum wear amount and the cutting tool life in test of turning AlSi7Mg2Sr003/SiC composite piston skirt. Additionally, the morphology of cutting tools and machined surface was also observed. Based on these studies, it was useful to choose the appropriate machining parameters in turning composite piston under industrial conditions.

These studies showed that PCD tools exhibited preferable wear resistance and cutting performance in cutting SiCp/Al composite materials. Both the size of diamond grains and SiC particles had a significant effect on tool wear and cutting performance. However, at the present, the related studies were still lacking on SiCp/Al composites with high volume fraction and small reinforced granules. In the whole green cutting environment, dry milling is receiving extensive attention. Furthermore, in the aspect of studying tool wear when PCD cutters were applied in dry milling silicon carbide particle–reinforced aluminum matrix composite materials, the cutting conditions are more severe. The corresponding conclusion has a direct guidance for wet milling. Therefore, under the condition of dry cutting and high-speed down milling, the experimental studies on the tool wear resistance and wear morphology were dissected, when PCD cutters with four different diamond granule sizes of 5, 10, 25, and 32 μm were adopted in machining SiCp/Al composites with small SiC granules and high volume fraction. The influence factors of change law of cutting forces and the machined surface roughness were also observed.

2 Experimental design

The machined specimen was SiCp/Al composite materials which the higher volume fraction was 45% and the size of smaller SiC particles was 5 μm. The single-tooth vertical PCD cutting cutters of diamond granule sizes of 5, 10, 25, and 32 μm were used in the experiments. All the PCD cutters were adopted in the same geometric structure, which the diameter of cutters is 16 mm and the radius of arc edge is 0.4 mm. The same geometric angles of cutters were applied in these experiments. For example, rake angle γ_0, clearance angle α_0, cutting edge angle κ_r, and cutting edge inclination angle λ_s were listed as 0°, 11°, 90°, and 5°, respectively. The material property of specimen is listed in Table 1. All the high-speed milling experiments were accomplished in the condition of dry cutting in CNC vertical machining center.

When PCD tools were used in machining SiCp/Al composite materials with higher volume fraction and smaller SiC grains, all the experiments were accomplished under the condition of using the same cutting parameters in order to study the tool wear characteristics and cutting performance PCD cutters with different diamond particle sizes. The used milling speed νc is 352 m/min (spindle speed n of 7000 r/min). The feed per revolution fr is 0.2 mm/r. The milling width ae and axial cutting depth ap is 12 and 0.5 mm. The local photos of the milling experiment and the measuring system of cutting forces are shown in Fig. 1.

In these experiments, we adopted the rotating measurement system of cutting forces manufactured by Swiss Kistler Corporation. As can be seen from Fig. 1, the measurement system consists of 9123C rotary dynamometer, RCD5223

Table 1 Material properties of specimen

Attribute parameter	Density (kg/m^3)	Elastic modulus (GPa)	Bending strength (MPa)	Yield strength (MPa)	Thermal expansion coefficient (°C^{-1})	Thermal diffusion coefficient (m^2/s)	Thermal conductivity (W/(m K))	Poisson ratio
Value	2950	156.4	629	343.5	12.2×10^{-6}	60.5×10^{-6}	138.1	0.26

signal conditioner, 5697A data collector, and computer. The signals of cutting forces Fx, Fy, and Fz in different directions and torque Mz can be collected in real time. The sampling frequency is set up 6000 Hz. In different cutting distances, the TR100 roughness meter was used to measure the machined surface roughness. Tool wear on flake face of PCD cutters was observed and analyzed by employing VHX-1000C super-depth digital microscope system.

3 Experimental results and analysis

3.1 Effects of diamond grain size on tool wear

As shown in Fig. 2, the cutting path of the milling cutter per revolution is circular arc when the vertical milling PCD cutters of diamond granule sizes of 5, 10, 25, and 32 μm, respectively, were applied in milling SiCp/Al (45 vol.%) composite materials with 5-μm SiC particle. Among them, Fc is resultant milling force on the active cutting plane. Fx and Fy are milling forces in directions X and Y, respectively. The milling width and feed speed of specimen are remarked as ae and vf, respectively. The radius of PCD tools r can be calculated as the formula, $r = D/2$. D means the diameter of milling tool. The calculation formula of cutting distance per revolution L is shown as follows.

$$L = \frac{\alpha}{360^{\circ}} \pi D$$

In the above formula, the corresponding central angle of cutting arc is α, which can be calculated as the following formula: $\alpha = 180^{\circ} - \arccos \frac{ae - r}{r}$.

As the cutting distance increases, the curves of the maximum tool wear amount VBmax on flake face of four different diamond granule sizes are shown in Fig. 3.

As can be clearly seen from Fig. 3, when PCD tools were adopted in cutting 45%SiCp/Al composites with smaller SiC granules, the maximum VBmax of wear amount on flake face of cutters with larger diamond grain sizes, such as 25 and 32 μm, is much less than that with smaller diamond granule sizes of 5 and 10 μm. That is to say, under the above experimental conditions, the tool wear resistance of larger diamond grain size is better than that of smaller diamond grain size, when milling SiCp/Al composites with smaller SiC particle size and larger volume fraction at a high speed. From the tool wear rate, at the initial stage of cutting, the tool wear rate with larger diamond grain is slower than that with smaller diamond grain. As cutting distance adds, the wear rate of PCD cutters of 5-μm diamond granule size is obviously higher than that of other three kinds of diamond granule size. When diamond grain sizes are 25 and 32 μm, the tool wear amount both increases more slowly.

The experiment results are different from the variation of maximum wear amount while high-speed cutting 56 vol.% SiC particles reinforced aluminum matrix composites with 60-μm larger SiC particle size. The PCD cutter with 5-μm diamond granules has the least tool wear amount. On the contrary, the maximum tool wear amount of particle size of 32 μm is the most [17].

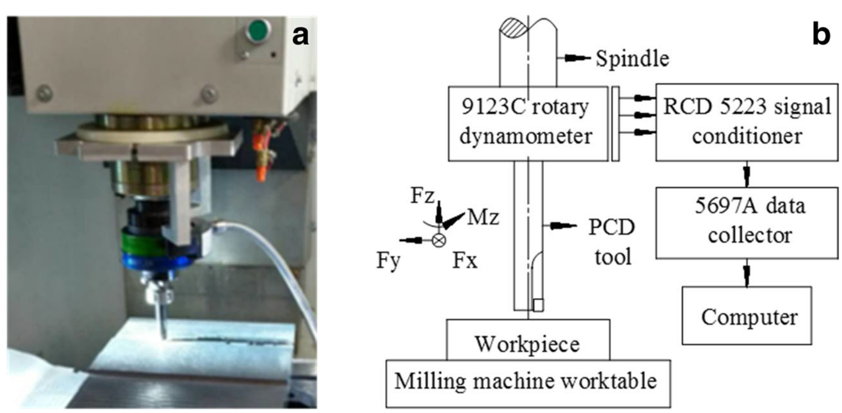

Fig. 1 **a**, **b** Photos of local experimental setup and measuring system

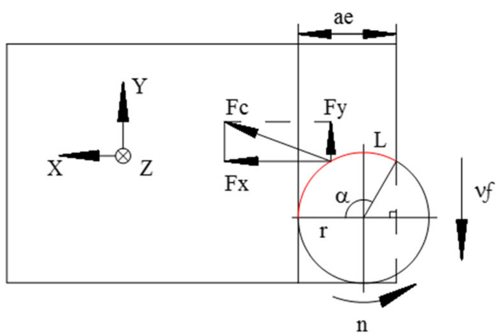

Fig. 2 Diagram of cutting path per revolution

The above experimental results demonstrate the differences of the wear resistance of PCD cutters with different diamond granule sizes when milling composites with 60- and 5-μm SiC grain sizes at high speed. It suggests that the wear mechanism of PCD cutters is different from each other.

When the size of SiC particles is 60 μm, larger SiC particles form an action of high-frequency impact and scribe on cutting tools. When diamond grains are larger, it is easier to break and fall off under the iterative action of impact and scribe of larger SiC granules. Moreover, the bigger diamond granules broke and fall off, followed by forming larger pits and groove marks in the dimension. Therefore, when SiC particle size is 60 μm in milling SiCp/Al composites at a high speed, the PCD tools of larger diamond granule size are more prone to wear [17].

However, when the size of SiC particle is 5 μm, the function of impact and crushing of smaller SiC particles on the diamond grains of PCD tools is not very large. The smaller SiC particles impact and scribe on PCD cutters in high frequency, resulting in that the cutting tools mainly suffer from mechanical fatigue wear. At this time, PCD tools with larger diamond grains have better wear resistance.

When PCD cutters with four different diamond granule sizes are employed to machine SiCp/Al composites with 5-μm small particle, the tool wear morphology of PCD cutters at the beginning of cutting (cutting distance Ls is approximately 200 m) and after accomplishment of cutting experiments is shown in Figs. 4 and 5, respectively.

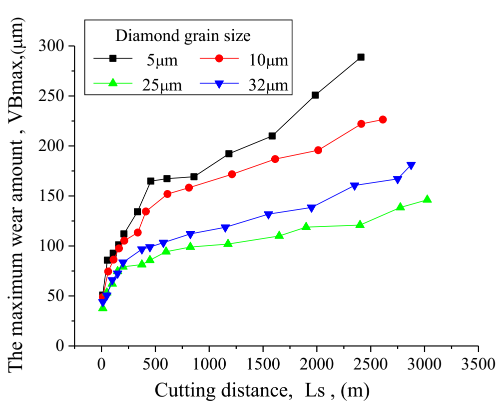

Fig. 3 The wear curves of PCD cutters of different diamond grain sizes

As can be clearly seen from Figs. 4 and 5, at the beginning of cutting, the tool wear of PCD cutters with 5-μm grain size is much more serious than that with other grain sizes. After the cutting experiments are completed, the tool wear of 5-μm grain size is the most serious all the same, followed by the granule sizes of 10 and 32 μm. The tool wear of granule size of 25 μm is the slightest. From the point of view of tool wear morphology in detail, the flake wear mainly distributes in the homologous parts of the arc edge and the minor flank face. It exists wear groove marks on the flake face. However, compared with cutting composites with large SiC granules and high volume fraction, the scale of wear groove marks is much smaller and the wear surface is more uniform. As the cutting distance increases, there are obvious wear pits near the junction of arc edge and main cutting edge. This is mainly because the diamond grains are more easily worn and shedding when cutting in PCD cutters of diamond granule size of 5 μm. When PCD milling cutter of 25-μm diamond granule size is utilized for machining 45%SiCp/Al composites with 5-μm SiC particle size at a high speed, due to the smaller SiC granule size and the slight function of impact and crack on the diamond particles, the diamond granules are not easy to fall off. The PCD cutters with larger diamond grains have better wear resistance. At present, the pits near the arc edge are the most inconspicuous. On the secondary flank face, it forms a slender wear zone, and the wear zone is wider when it is closer to the position of the arc edge. No matter at the beginning or at the completion of cutting, the spindly wear zone is the most uniform while the diamond granule size is 25 μm. For the PCD cutters with granule size of 32 μm, maybe due to the larger diamond granule size or the decrease of its strength, it occurs with slight damage under the action of fatigue impact of 5-μm SiC particles. Based on the above reasons, the tool wear resistance of 32-μm grain size is slightly lower than cutters of 25-μm diamond grains.

Compared with the tool wear morphology during cutting materials with 56 vol.% and 60-μm SiC granules, the cutting edge and the arc blade are relatively smooth throughout the cutting process. All the milling cutters have no obvious chipping phenomenon. This is mainly because SiC particles are smaller, and most of SiC particles are covered by softer Al matrix, resulting in the function of impact on the diamond grains which is little in the milling process.

When machining SiCp/Al composite materials with 45 vol.% and SiC grain size of 5 μm, the experimental results indicate that a larger adhesion of machined material occurs on the flake face of all PCD tools, but it does not form built-up edge, as shown in Fig. 6. But when milling composites with 56 vol.% and 60-μm SiC granule size, the adhesion of machined materials on the cutting cutters is very small. From the comparison of the tool wear resistance of PCD cutters in milling process of these two different SiCp/Al composites, when SiC granule size is 5 μm and volume fraction is 45%,

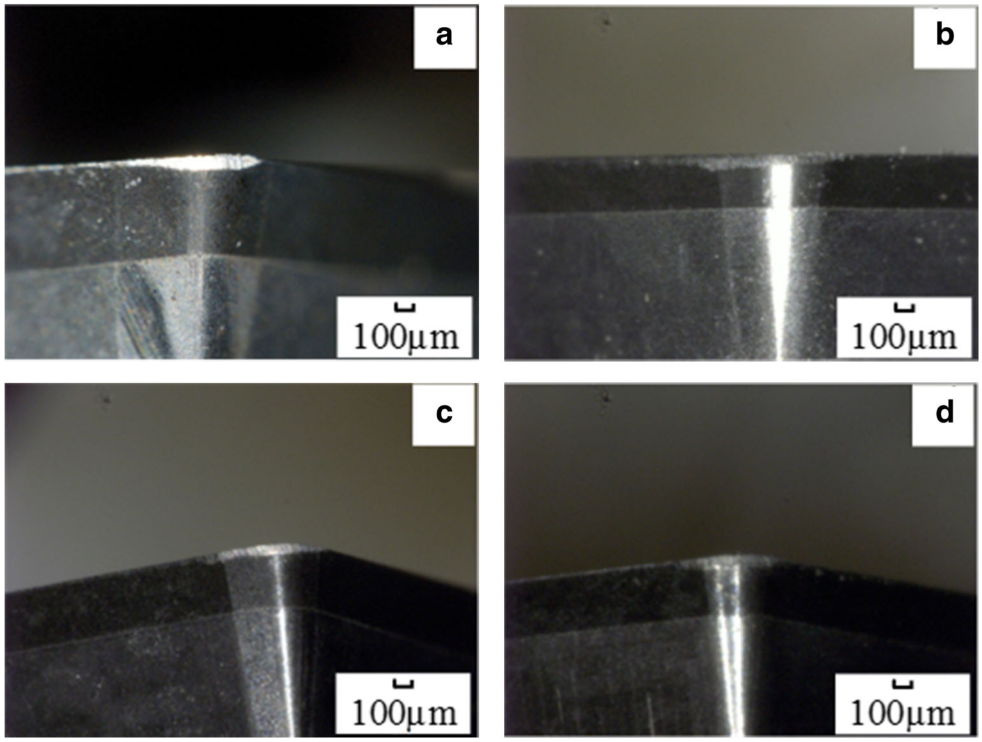

Fig. 4 Wear morphology of PCD cutters at the beginning of cutting. **a** Diamond grain size is 5 μm. **b** Diamond grain size is 10 μm. **c** Diamond grain size is 25 μm. **d** Diamond grain size is 32 μm

the wear resistances of all PCD cutters are far higher than those of tools in milling process of composites with 56 vol.% and granule size of 60 μm [17]. The difference of volume fraction of SiC grains of workpiece materials is one side reason. On the other side, SiC particles of 5 μm are small, and most of SiC particles are covered by Al matrix in the milling process. Not only the effect of tool wear lessens, but also the workpiece materials are more easily to adhere to the flake face of PCD cutters, making a certain protective function on the cutting cutters.

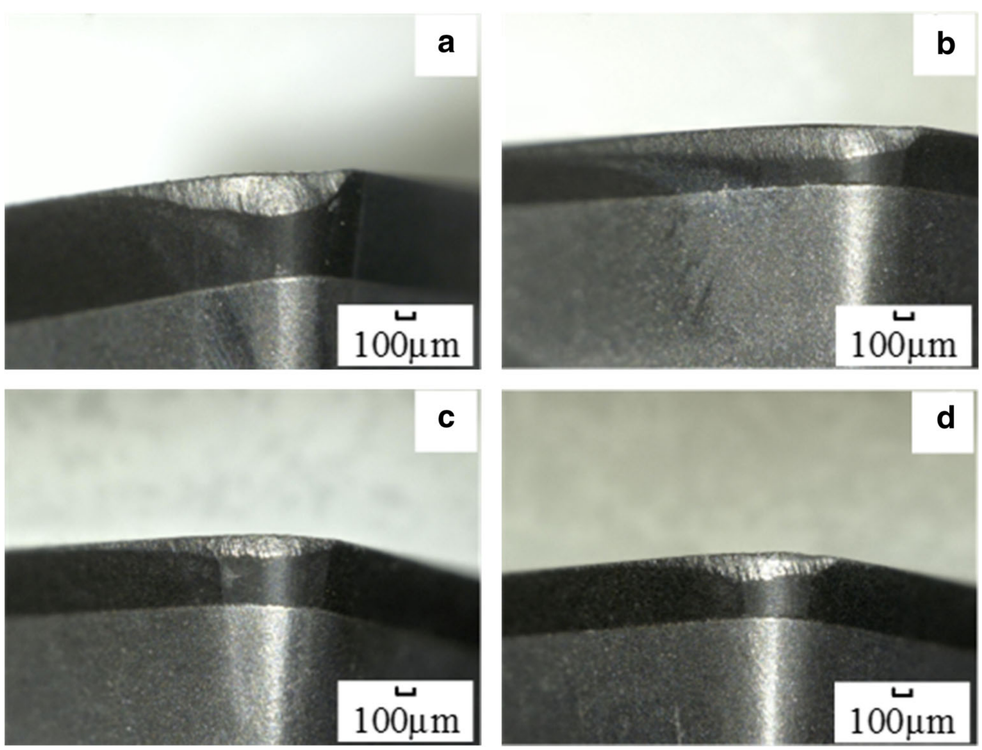

Fig. 5 Wear morphology of PCD cutters after accomplishment of cutting experiment. **a** Diamond grain size is 5 μm. **b** Diamond grain size is 10 μm. **c** Diamond grain size is 25 μm. **d** Diamond grain size is 32 μm

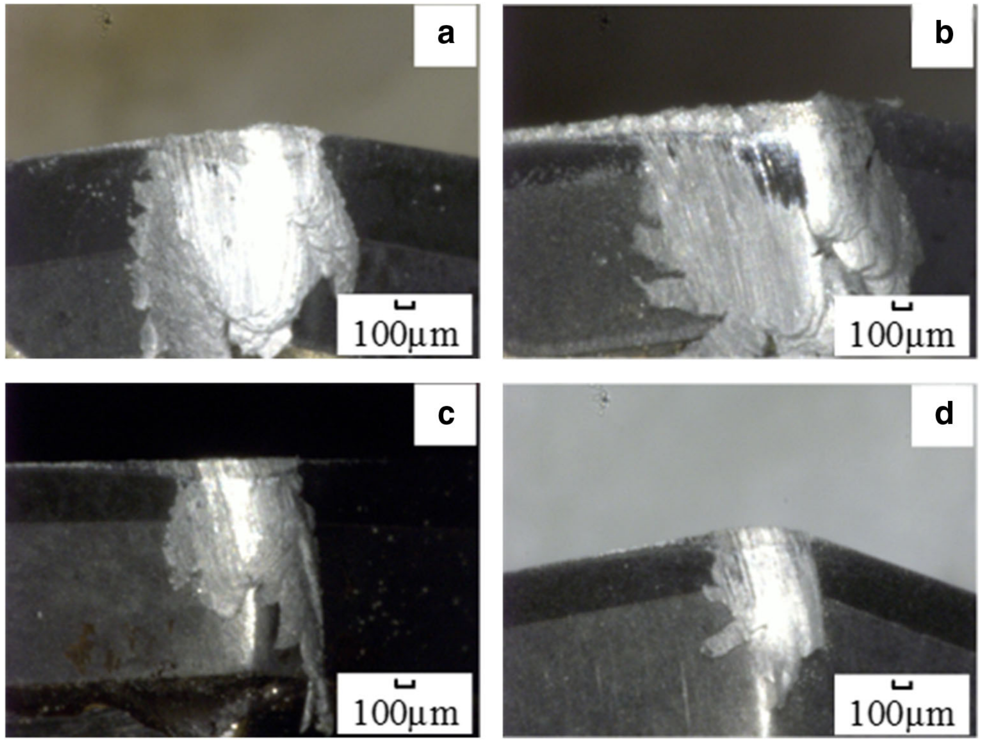

Fig. 6 The adhesion of the machined material on the cutter. **a** Diamond grain size is 5 μm. **b** Diamond grain size is 10 μm. **c** Diamond grain size is 25 μm. **d** Diamond grain size is 32 μm

3.2 Effects of diamond grain size on cutting forces

When PCD cutters with four different diamond grain sizes are applied in high-speed machining SiCp/Al composites, the variation curves of cutting forces (Fx, Fy, Fz) in three different directions (*X*, *Y*, *Z*) and torque Mz with the increment of cutting path are shown in Fig. 7. In Fig. 7, the values are obtained by intercepting time-domain signal during the stable cutting stage and calculating the average of the peak value in 10 cycles.

In Fig. 7, as cutting distance increases, the cutting forces (Fx, Fy, and Fz) in the *X*, *Y*, and *Z* directions all show curved rising trend when PCD tools of four different grain sizes are applied in milling SiCp/Al composites. Both cutting force components Fx and Fy are significantly larger than Fz. Such upward trend of Fz is more monotonous and obvious. Comparing the variation law of corresponding cutting forces of four different diamond grain sizes, it can be found that when using diamond granule sizes of 5 and 10 μm, cutting forces' increasing amplitude with the increment of cutting path is higher than diamond particle sizes of 25 and 32 μm. Such these trends have a good correspondence with the curves of tool wear in Fig. 3, especially the variation law of axial force Fz is more obvious. The torque Mz also increases with the cutting distance as a whole, but the rising trend is not significant and existing fluctuation. From the numerical value of cutting force components and torque, in general, the cutting forces and torque of PCD tools of larger diamond grains are less than those of smaller diamond grains. Especially, the phenomenon of differentiation is more obvious in the late cutting stage. There are mainly two aspects of reasons for showing such change rules. On the one hand, it is related to the better wear resistance of PCD cutters with large diamond granules when machining composite materials with smaller SiC particles and higher volume fraction. On the other hand, the larger the diamond particle size, the smaller the friction and adhesion between diamond grains and machined material.

Figure 8 shows the intercepted time-domain signals of axial force Fz of four different diamond grain sizes in 10 cutting periods, when cutting distance Ls is about 2500 m. In Fig. 8, when diamond particles are larger, such as 25 and 32 μm, the axial force Fz is significantly smaller than the corresponding values of small diamond particles, such as 5 and 10 μm. And the fluctuation of cutting force signals is also smaller at the stage without taking part in cutting among each cutting period. This is corresponding with the variation rule of axial force Fz with the diamond particle size, while the cutting distance is close to the cutting distance in Fig. 7.

3.3 Effects of diamond grain size on the machined surface roughness

When PCD cutters of different diamond granule sizes are adopted in machining 45%SiCp/Al composites with small SiC granules at a high speed, the machined surface roughness varies with the addition of cutting path, as shown in Fig. 9.

As can be observed from Fig. 9, when the PCD cutters of four different diamond grain sizes are applied in high-speed

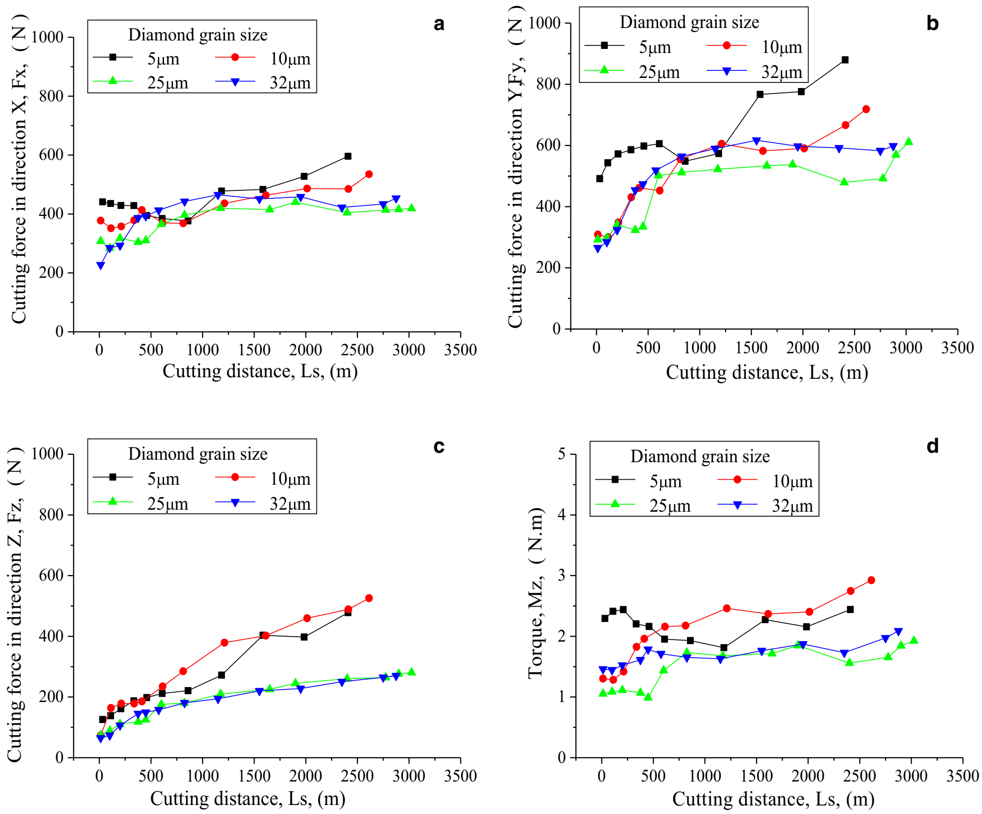

Fig. 7 Cutting force vs. cutting distance. **a** Fx. **b** Fy. **c** Fz. **d** Torque Mz

milling composites with 45 vol.% and smaller SiC granules, the preferable machined surface roughness can be acquired, which is significantly better than the values when cutting composites with 56 vol.% and 60-μm larger SiC granules [17]. And the machined surface roughness shows a decreasing trend overall as the cutting distance added. In particular, while cutting composites using diamond granule size of 25 μm, the machined surface roughness varies relatively gently. And the values are also smaller, basically ranging among 0.2 and 0.4 μm. At the late stage of cutting, the machined surface

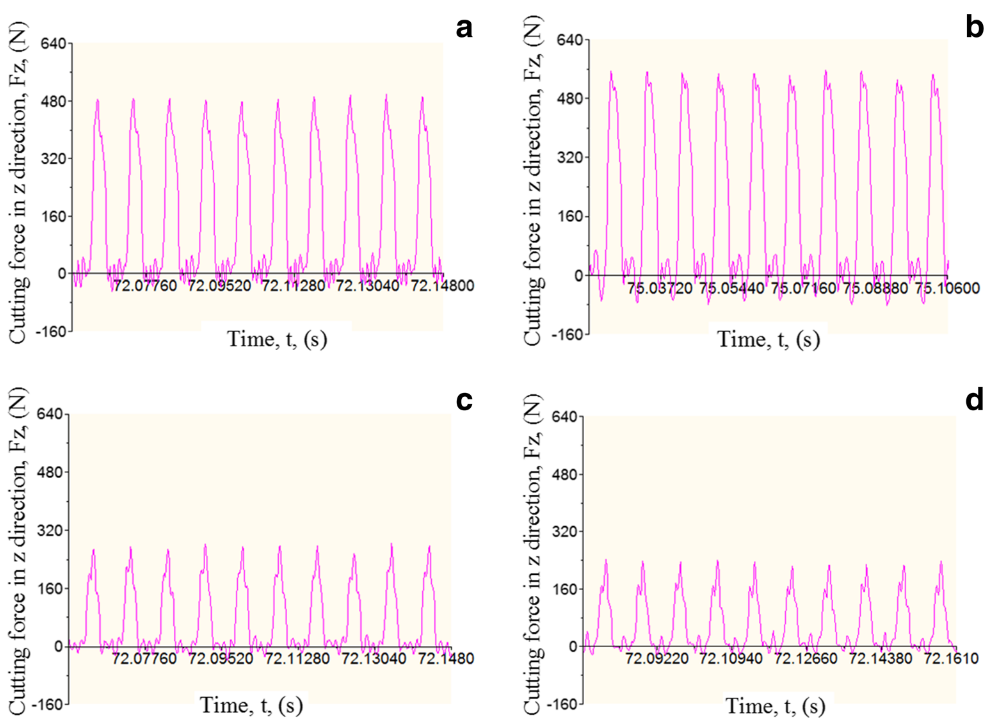

Fig. 8 Time-domain signal of Fz of different diamond grains. **a** Granule size is 5 μm. **b** Granule size is 10 μm. **c** Granule size is 25 μm. **d** Granule size is 32 μm

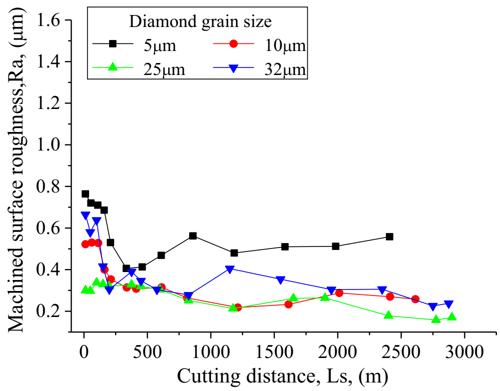

Fig. 9 Machined surface roughness vs. cutting distance

reaches a smooth surface of Ra 0.2 μm. When the sizes of diamond granules are 10 and 32 μm, the machined surface roughness is also small. The machined surface roughness is higher than other granule sizes, while diamond granule size is 5 μm. Within above experimental conditions, on the one hand, the uniform tool wear can extrude and iron on the machined surface. It is presented as the decreasing trend of machined surface roughness as cutting distance increased. On the other hand, the tool wear of PCD cutters will also aggravate the adhesion of specimen material on the cutters, resulting in the increase of machined surface roughness. This is why the machined surface roughness is larger when cutting with PCD tool of diamond granule size of 5 μm.

4 Conclusions

When using PCD cutters with four different diamond particle sizes in machining silicon carbide particle–reinforced aluminum matrix with 45 vol.% and 5-μm SiC granule size at a high speed, several experimental studies on the tool wear characteristics, the variation of cutting forces, and machined surface roughness were acquired as follows.

1. When SiCp/Al composites with higher volume fraction (45%) and smaller particle size (5 μm) are high-speed milled by adopting PCD cutters of diamond granule size of 5, 10, 25, and 32 μm, respectively, all the milling cutters' wear resistance is far higher than that of PCD cutters during machining SiCp/Al composites with 56 vol.% and 60-μm SiC granule size. The tool wear amount of PCD cutters of larger diamond grain sizes, such as 25 and 32 μm, is much significantly smaller than the value of small diamond particles, such as 5 and 10 μm. And the former wear rate is also lower. Within the cutting range, the tool wear resistance of 25-μm diamond particle size is the best, followed by granule sizes of 32 and 10 μm. The wear resistance of diamond granule size of 5 μm is the worst. This is opposite to the conclusion that the tool wear of diamond granule size of 5 μm is the least and the tool wear amount of 32 μm granule size is the biggest, while high-speed milling composites with 56 vol.% and 60-μm SiC particles.
2. During high-speed machining SiCp/Al composite materials with 45 vol.% and 5-μm SiC granules, the tool wear morphology is flank wear and slight wear groove marks. There is no chipping of cutting edge and coarse wear groove marks due to the small SiC particles and slight function of impact and crack on the diamond grains. It forms a large amount of adhesion of machined materials in the cutting process, but built-up edge is not formed.
3. The cutting forces Fx, Fy, and Fz and torque Mz all show the variation trends of ascent curve with the increment of cutting path. Especially, the upward trend of axial force Fz is more monotonous and obvious. In general, the cutting forces and torque of PCD tools of larger diamond grain size are smaller than those of smaller diamond grain size. The phenomenon of differentiation is more obvious at the end of cutting stage.
4. Using PCD cutters of four different diamond granule sizes in high-speed milling composites with smaller SiC granules and higher volume fraction, the preferable machined surface roughness all can be acquired. While diamond granule size is 25 μm, the machined surface roughness Ra is the minimum. The machined surface roughness using diamond granule size of 5 μm is higher than that using other diamond granule sizes. In general, the machined surface roughness decreases when the cutting distance increases.

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