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ORIGINAL ARTICLE

Study on characteristics of SiCp/Al composites during high-speed milling with different particle size of PCD tools

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Abstract SiCp/Al composites contain a large amount of SiC particles as reinforced phase, and the particles are hard and brittle. So tool wear is quite serious in the cutting process. Polycrystalline diamond (PCD) tools are the most effective tool material for achieving high-speed and precision cutting of SiCp/Al composites. In this paper, PCD tools were used in high-speed milling SiCp/Al composites with higher volume fraction and larger size SiC particles. The wear resistance and wear mechanism of PCD tools were studied when the diamond particle sizes were 5, 10, 25, and 32 μm, respectively. Moreover, the variation characteristics of cutting force and machined surface roughness were investigated. The results showed that the size of diamond particle had a great influence on wear resistance of PCD tools. During high-speed milling SiCp/Al composites with high volume fraction and larger particle size, the larger the particle size of diamond particles were, the worse the wear resistance of PCD tools were. With the increase of diamond particle size, the flank wear increased, and the degree of micro-chipping of cutting edge deepened slightly. The values of cutting force and machined surface roughness were both smaller, when diamond particle size of PCD tools was 5 μm. There was hardly variation of machined surface roughness in the whole cutting process. In other words, the tool wear had little impact on the machined surface roughness.

Keywords High-speed milling · SiCp/Al composites · PCD tools · Particle size · Tool wear

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1 Introduction

SiCp/Al composite materials have some excellent advantages, including high-specific strength, high-specific rigidity, high-specific modulus, low thermal expansion coefficient, good thermal conductivity, superior wear resistance, and isotropy [1, 2]. Compared with traditional alloy materials, they also have incomparable design ability. With continuous improvement of the level of preparation process technology and material properties, SiCp/Al composites are increasingly widely used in the fields of national defense and civilian, such as aerospace, electronic communication, electronic packaging, and automobile [3–5]. SiCp/Al composites illustrate broad application prospects and great development potential. However, SiCp/Al composites are known as one kind of difficult-to-machine materials because of containing a large amount of hard and brittle SiC particles. There are two urgent problems to solve in the process of high-speed milling, which are severe tool wear and low surface quality [6–8].

Over the previous researches, there were a lot of studies on the suitable cutting tool for machining SiCp/Al composites. Seeman [9] studied the effect of machining parameters on tool wear and surface roughness when uncoated carbide tool (K10) was used in turning 20% SiCp LM 25Al composites. Bian et al. [10] investigated wear characters of a single flute

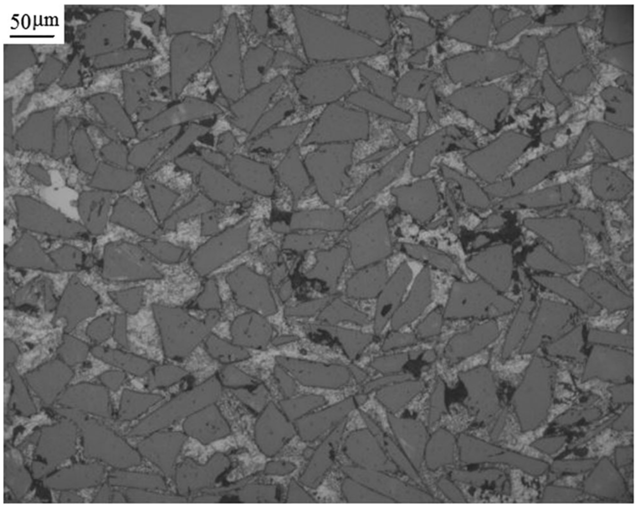


Fig. 1 Microstructure of SiCp/Al composites

monocrystalline diamond tool in precision milling of SiCp/Al composite materials with high volume fraction (65%) and larger particle size. The remove method of materials and machined surface quality were also investigated. Santos Jr. et al. [11] pointed out PCD tools which were one of the most recommended for machining aluminum containing SiCp particles. Huang et al. [12, 13] found that cermet cutting tools, TiN-coated tools, and cemented carbide tools would all be seriously worn quickly in milling 56% SiCp/Al composites.

They also have investigated wear characteristics of PCD tool and TiC-based cermet tool during milling 56% SiCp/Al composites with large SiC particles. Ge et al. [14] compared the cutting performance of straight-nose SCD, round edge SCD, and PCD tools during turning SiCp/2009Al (15%) composites. It was found that PCD tools had a steady cutting performance. These results indicated that PCD tools were the most suitable for high-speed and precisely machining SiCp/Al composites.

Furthermore, several literatures have been concerned with the effect factors on the machinability performance of PCD cutting tools during cutting SiCp/Al composites, such as diamond grain size and geometric parameters of cutting tools, cutting parameters, and properties of machined materials. Quan et al. [15] indicated that SiC particle size and volume fraction were the main factors on tool wear by comparing tool wear curves of different types of cutting tools during cutting SiC/A356 with different particle sizes (42, 85, and 2 μm). Yang and Han et al. [16, 17] focused on the influence of grain sizes and geometrical structure of PCD tools on tool wear and machined surface quality when high-speed milling SiCp/Al composites with high volume fraction (65%) and 60–80-μm size of SiC particles. They illustrated that the wear resistance of PCD tools with grain size of 0.5~1 μm was better than that of 2~30 μm. Wang et al. [18] studied performance of PCD tool with the same grain size in high-speed milling of SiCp/Al composites with 65% volume fraction and 10-μm particle size. The results indicated that PCD grain size was one of the most important factors of tool performance. Muthukrishnan et al. [19, 20] found that high cutting speed and lower feed rate could be useful for obtaining superior surface roughness and minor flake wear in turning A356/SiC/10p with PCD 1500 grade inserts. The effects of three grades of PCD inserts on the tool wear morphology, specific power, and surface finish of machined workpiece in turning (15%) Al-SiC metal matrix composites were also examined. The results showed that 1600 grade PCD inserts performed better than 1500 and 1300 grade PCD inserts.

However, the adaptability and wear resistance of PCD tools are still lack of researches during milling SiCp/Al composites with high fraction volume and large particle size. In this paper, wear resistance and wear mechanism of PCD tools were studied in high-speed milling SiCp/Al composites, when the diamond particle sizes are 5, 10, 25, and 32 μm, respectively. The influences of diamond particle size on the cutting force and the machined surface roughness were also analyzed.

Table 1 Material properties of SiCp/Al composite

Material	Density (g/cm^3)	Elastic modulus (GPa)	Specific modulus (m)	Bending strength (MPa)	Thermal conductivity (W/m·K)	Poisson ratio
SiCp/Al	2.94	213	72.4×10^5	410	235	0.23

Table 2 Geometric parameters of PCD tools

Geometric angle	Rake angle γ_o (°)	Clearance angle α_o (°)	Cutting edge inclination angle λ_s (°)	Cutting edge angle k_r (°)	Minor cutting edge angle k_r' (°)
Designing angle	0	11	5	90	0
Working angle	− 9	20	5	90	0

Fig. 2 Experimental setup

2 Experimental conditions

The microstructure of composite material is shown in Fig. 1. It can be seen that the volume fraction of SiC particles is higher and the content is about 56%. The average size of SiC particles is about 60 μm. The physical and mechanical properties of SiCp/Al composites can be obtained from Table 1. In order to analyze the effect of diamond particle size on tool wear feature, the PCD tools with different diamond particle size were chosen. The particle sizes are 5, 10, 25, and 32 μm, respectively. Meanwhile, the same tool parameters were adopted in the experiments for advoiding the influence of cutter geometry parameters. And the used tool angles were listed clearly in Table 2. In addition, the tool diameter is 16 mm, and the corner radius is 0.4 mm.

In this paper, all the experiments were carried out with the same cutting parameters as follows. The cutting speed is 352 m/min. The feed rate is 0.2 mm/z, and the axial cutting

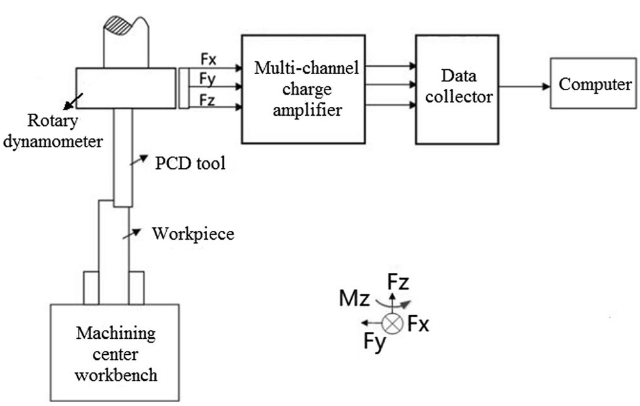
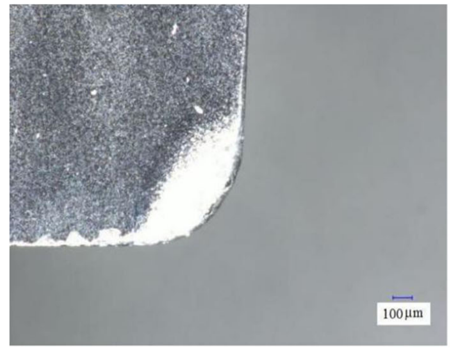
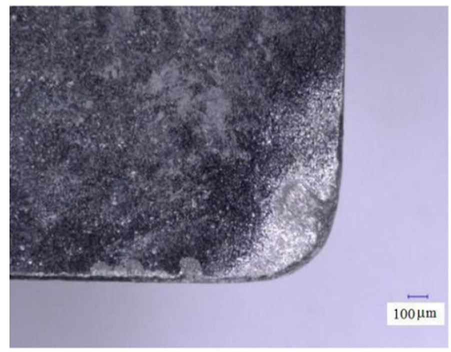


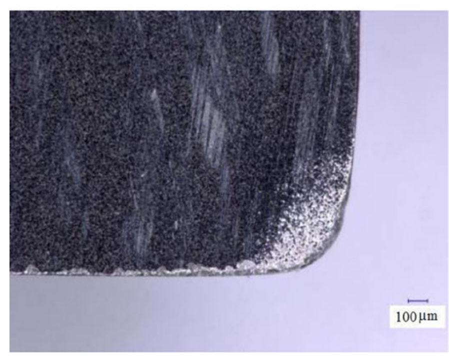
Fig. 3 Cutting force measurement system



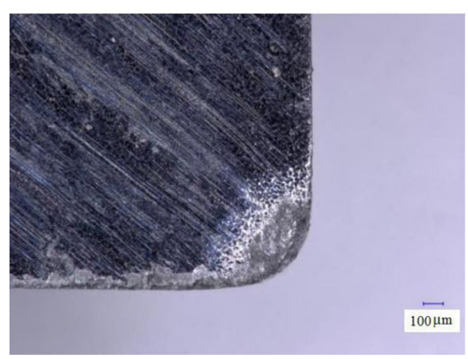
(a) Particle size of 5μm (L=47895mm)



(b) Particle size of 10μm (L=47707mm)



(c) Particle size of 25μm (L=48690mm)



(d) Particle size of 32μm (L=47100mm)

Fig. 4 Wear morphology on rake face of PCD tools with different particle size

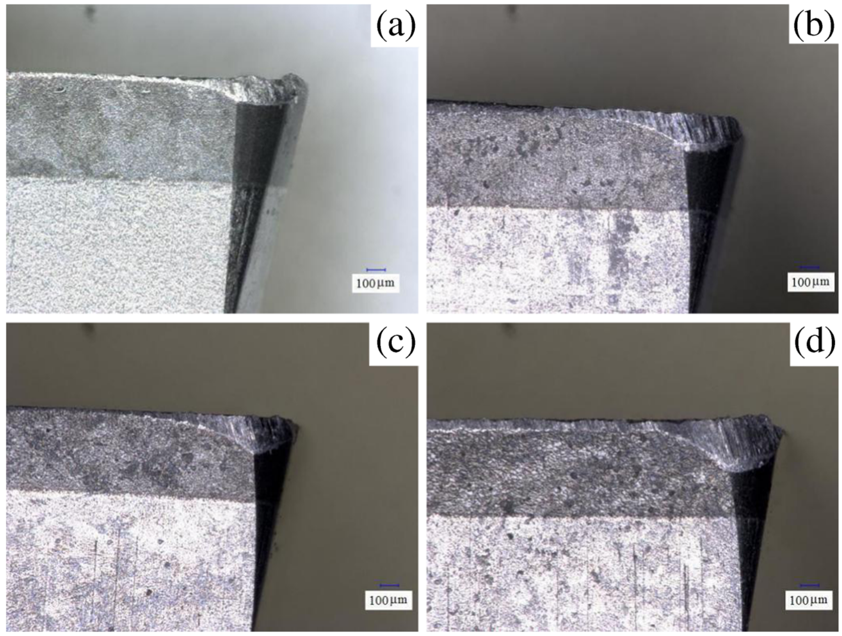


Fig. 5 Wear morphology on flank face of PCD tools with different particle size. **a** Particle size of 5 μm (L = 47,895 mm). **b** Particle size of 10 μm (L = 47,707 mm). **c** Particle size of 25 μm (L = 48,690 mm). **d** Particle size of 32 μm (L = 47,100 mm)

depth is 0.5 mm. Moreover, dry and high-speed milling is performed, and the cutting method is all down milling.

SiCp/Al composites were machined by CNC vertical machining center as shown in Fig. 2. Because the maximum speed of spindle can reach 8000 r/min, it is enough to realize high-speed milling. For the purpose of observing the change law of cutting force, the measuring system was adopted in the experiments as shown in Fig. 3. The measurement system of cutting force consists of RCD5223 multi-channel charge amplifier, 9123C rotary dynamometer, and 5697A data collector and computer. In order to obtain valid cutting force signals, the sampling frequency was set up to 3000 Hz. Moreover, we can observe the wear micro-topography of PCD tools with different diamond grain size by using VHX-1000C super-depth microscope. Machined surface roughness can be measured by the metering instrument of TR100 surface roughness.

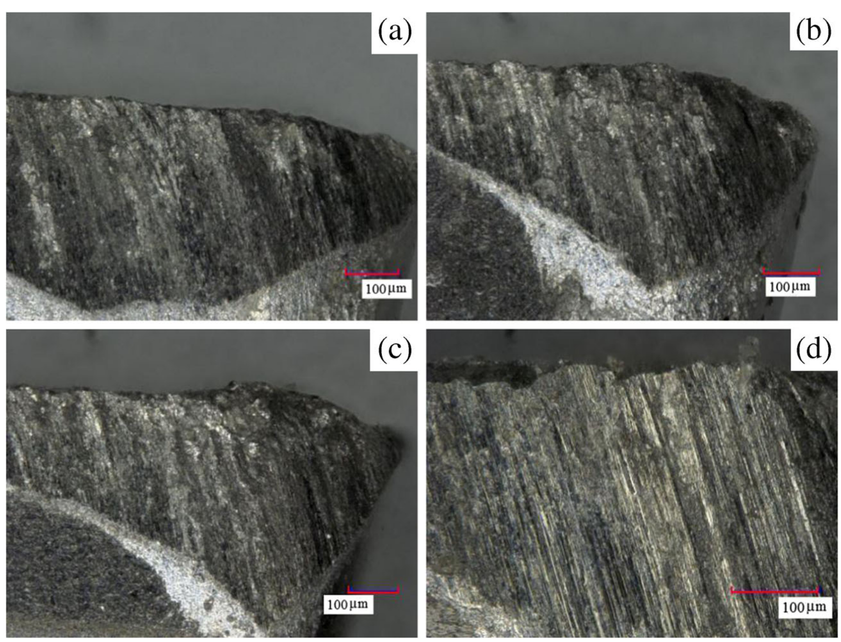


Fig. 6 The enlarged flank wear morphology of PCD tools with different particle size. **a** Particle size of 5 μm (400 times). **b** Particle size of 10 μm (400 times). **c** Particle size of 25 μm (400 times). **d** Particle size of 32 μm (700 times)

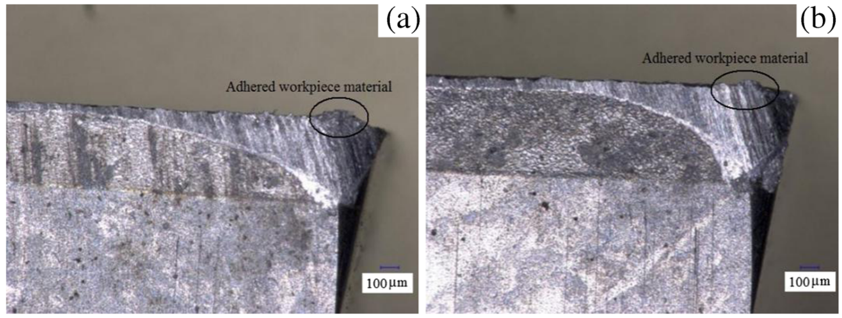


Fig. 7 The machined material adhered on the cutting edge. **a** Particle size of 25 μm. **b** Particle size of 32 μm

3 Experimental results and discussions

3.1 Tool wear characteristics and wear mechanism

3.1.1 Wear morphology characteristics and formation mechanism

Figure 4 shows the rake wear morphology of PCD tools with different diamond particle size, when the cutting distance fluctuates around 48,000 mm. From Fig. 4a–d, there are no obvious wear marks on the cutting zone of rake face, but there are micro-chipping phenomena in different degrees on the cutting edge. Besides, it can be seen that the degree of micro-chipping increases with the increase of diamond grain size. Obviously, when the grain size is 32 μm, the chipping phenomenon of PCD tools is the most serious, and the degree of micro-collapse is evidently greater than that of other grain sizes, as shown in Fig. 4d.

Figure 5 shows the flank wear morphology of PCD tools with different particle size. It is obvious that the wear zone on flank face mainly occurs in the corresponding circular arc edge. It forms the highest wear point at the intersect part between the side cutting edge and the circular arc edge, and it also forms a more uniform and slender wear region on the secondary flank face. This is mainly because that the corner radius r_ε (0.4 mm) is close to the adopted cutting depth (0.5 mm). Compared with the flake wear morphology of PCD tools with different particle size, the tool wear on flake face becomes more serious with the increase of diamond particle size. The flake wear is also the most serious when the particle size is 32 μm. All in all, it is clear that the diamond particle size has a direct effect on tool wear of PCD tools, when the SiCp/Al composites are machined at a high speed and a low feed rate.

Figure 6 shows the enlarged figures of wear morphology on flank face in order to observe more clearly. Compared with the four flake wear patterns, when diamond particle size is 5 μm, the cutting edge is smooth and the wear marks on flank face is small. With the increase of diamond particle size, the unevenness of cutting edge increases accordingly as well as the wear marks on flake face. Especially, when the diamond grain size of PCD tools is 32 μm, the phenomena described previously are both the most obvious among the four grain sizes. From the wear marks on flake face, this is mainly because of the mechanical fatigue wear and diamond particles' micro-cracking and shedding, when PCD tools are impacted and scribed by larger SiC particles in a high frequency. Obviously, when the diamond particle size is larger, it is more prone to cracking and shedding under the repeated impact of SiC particles. After the larger diamond particles crush and drop, the pits and groove marks with larger dimension are compelled to appear, as shown in Fig. 4d.

Furthermore, when the diamond particle size of PCD tools is larger, the machined material is easier to be adhered to the rake face near the cutting edge after the occurrence of micro-chipping of cutting edge. It forms gradual adhesion accumulation with compact mechanical bonding on rake face and occurs frequent shedding subsequently. Thereby, the degree of the phenomenon of micro-chipping further aggravates. The phenomenon adhesion accumulation can be both seen distinctly in the Fig. 7, when the diamond particle sizes are 25 and 32 μm.

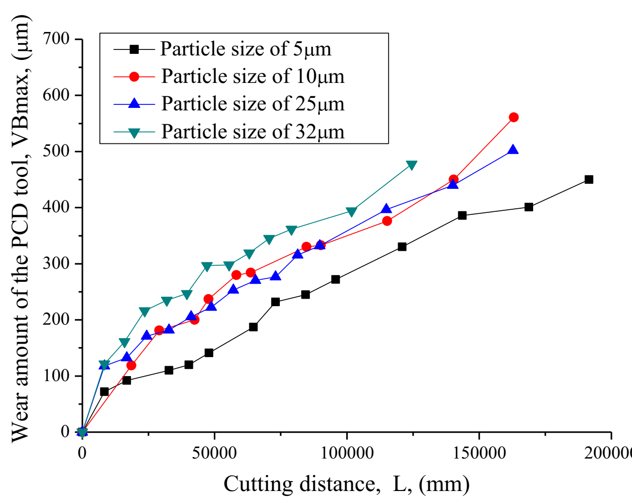
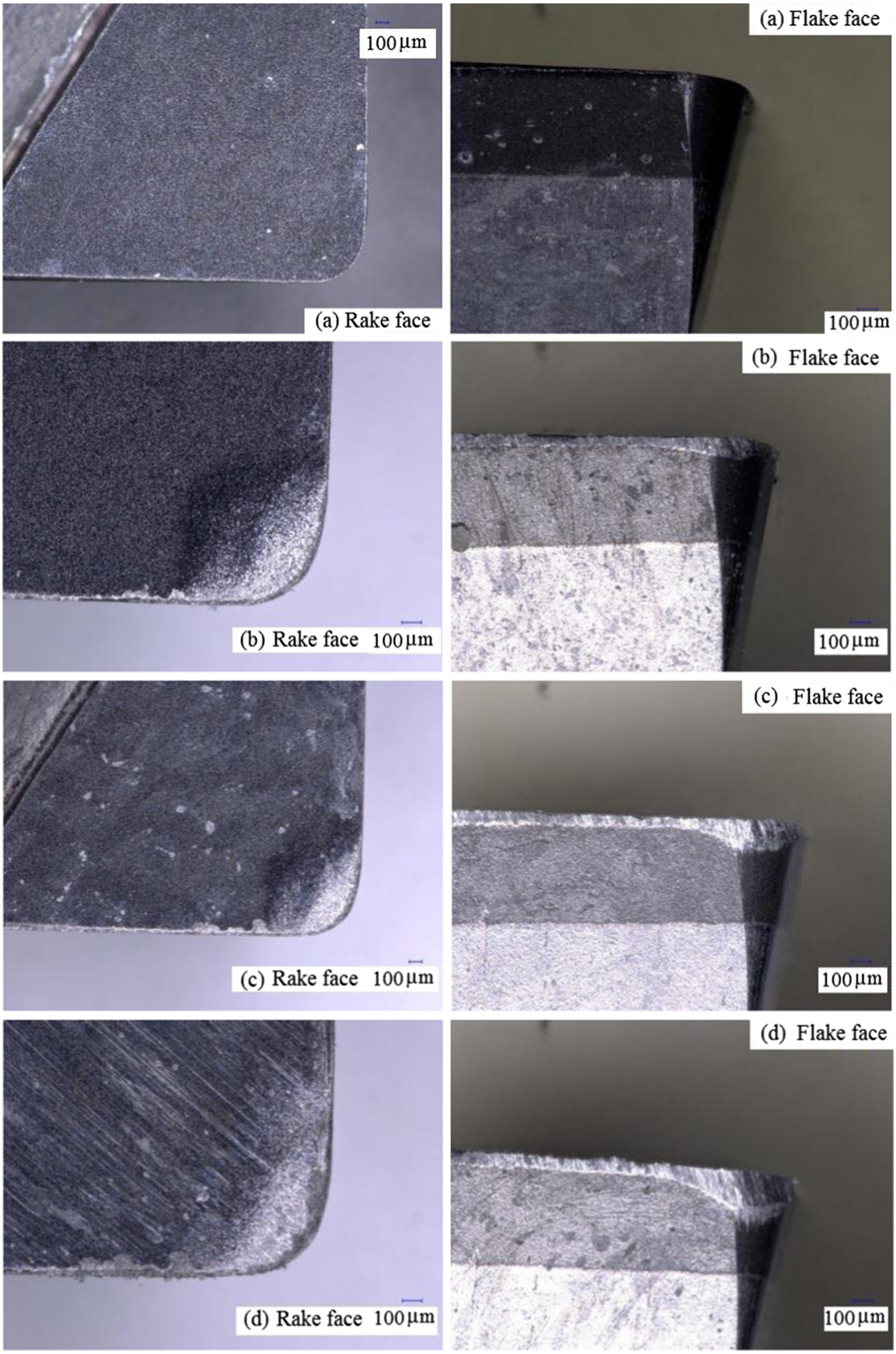


Fig. 8 The relation curves between cutting distance and tool wear of PCD tools with different particle size


100 μm
(a) Rake face
(a) Flake face
100 μm
(b) Flake face
(b) Rake face 100 μm
100 μm
(c) Flake face
(c) Rake face 100 μm
100 μm
(d) Flake face
(d) Rake face 100 μm
100 μm

◀ **Fig. 9** The transformation of wear morphology on rake face and flank face of PCD tools with the diamond particle size of 10 μm. **a** $L = 0$ mm. **b** $L = 18{,}517$ mm. **c** $L = 29{,}062$ mm. **d** $L = 58{,}252$ mm. **e** $L = 90{,}142$ mm, **f** $L = 115{,}282$ mm. **g** $L = 163{,}177$ mm

3.1.2 Comparison of wear resistance of PCD tools with different particle size

Figure 8 shows the wear curves of PCD tools with different particle size in high-speed milling of SiCp/Al composites. In Fig. 8, the wear amount represents the maximum wear value on flank face, and it is named VBmax.

From Fig. 8, it can be seen that tool wear amount is the smallest when diamond grain size is 5 μm. The wear amount is the maximum when particle size is 32 μm. When particle sizes are 10 and 25 μm, the value falls in between both. In other words, the wear amount increases with the addition of diamond grain size in the process of high-speed milling SiCp/Al composites with high volume fraction (56%) and SiC particle size of 60 μm. Besides, the maximum width VBmax of wear region on flank face grows at different rate during the initial cutting period. And the corresponding cutting distance at a higher wear rate is also different. Among the four wear curves, when the particle size is 32 μm, the wear

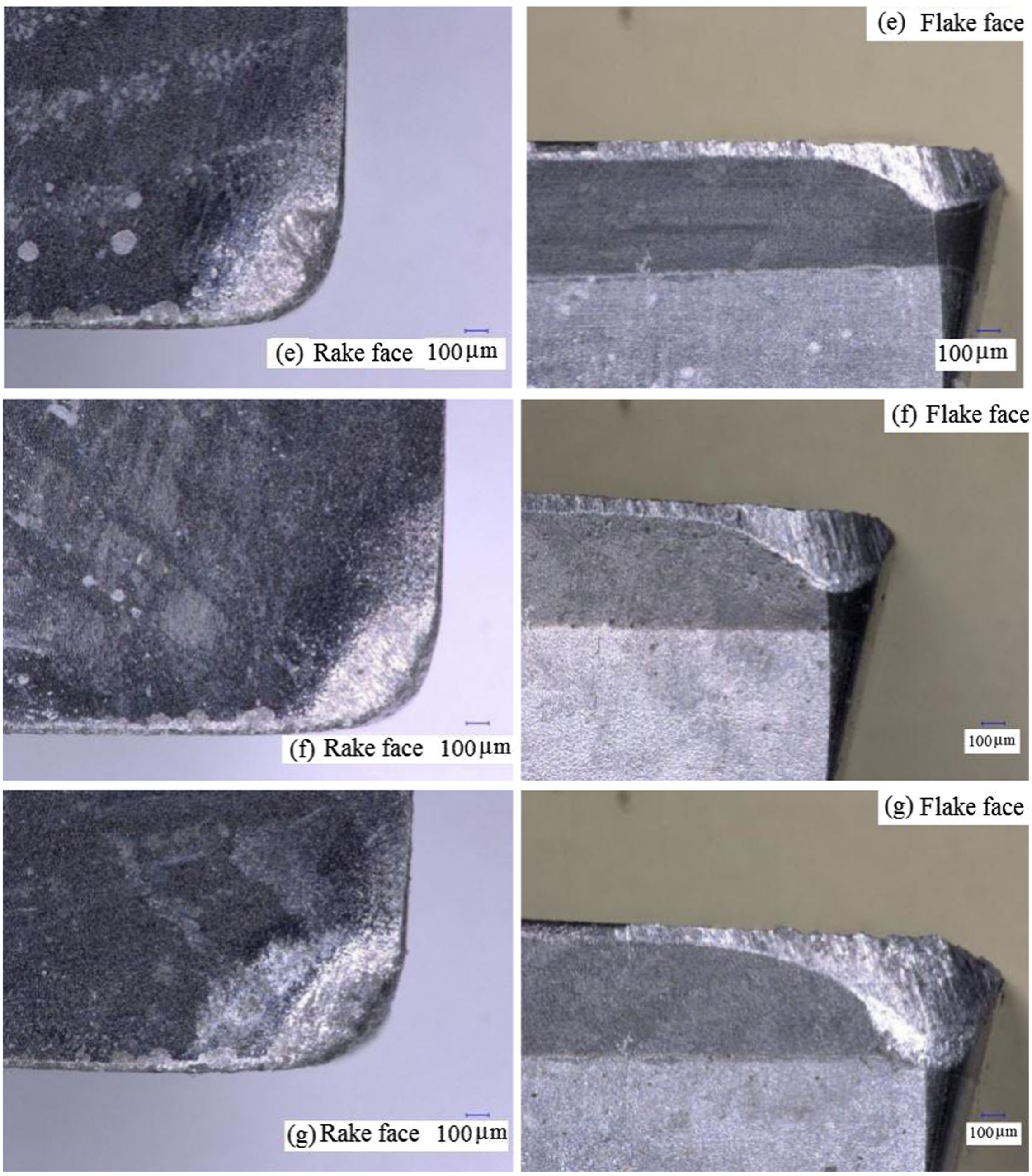


Fig. 9 (continued)

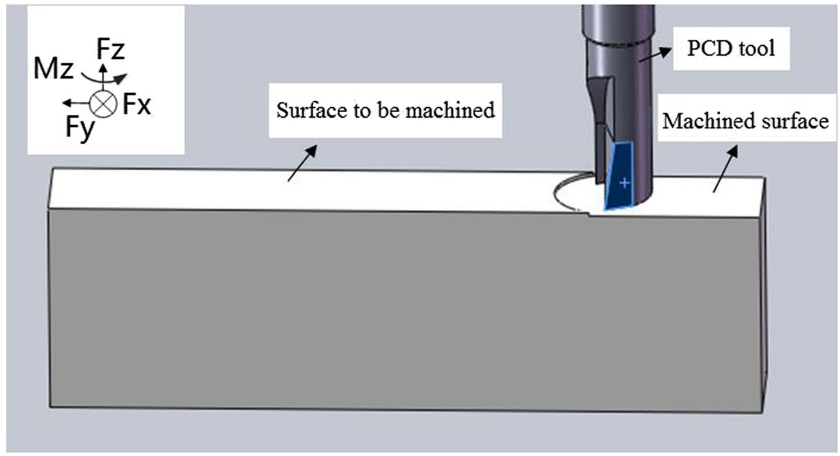


Fig. 10 Schematic diagram of direction of cutting force

rate is larger than that of other particle sizes within the cutting distance of 25,000 mm. That is to say that there is a more obvious severe initial wear stage. On the contrary, when the diamond particle size is 5 μm, the wear rate is lower than that of other particle sizes during the initial wear stage, and the corresponding initial cutting distance with severe wear is relatively shorter. Moreover, the wear rate of PCD tools is smooth in the full cutting distance. After the tool wear enters into a stable wear status, the wear rate of PCD tools with different particle size is almost the same. Based on the analysis of above parts, it is considered that the wear of PCD tools is mainly caused by the mechanical fatigue wear and the micro-cracking and shedding of diamond particles under the action of high-frequency impact scoring of large SiC particles when cutting SiCp/Al composites with high volume fraction and particle size of 60 μm. When the diamond particle size is 32 μm, the occurrence probability of crushing and falling is higher, so the tool wear amount is larger. However, when the diamond particle size is 5 μm, the occurrence probability of breakage is little because of small particle size. Even if it breaks or falls, the scale and influence are slight. So the corresponding tool wear amount is smaller. When the diamond particle sizes of PCD tools are 10 and 25 μm, there are two main reasons for making the degree of tool wear little difference between the two. On the one hand, the diamond particles with size of 25 μm are more easily to be impacted and broken than those with size of 10 μm. On the other hand, the scale influence of breaking is equivalent to that of the overall shedding caused by impacted when particle size is 10 μm.

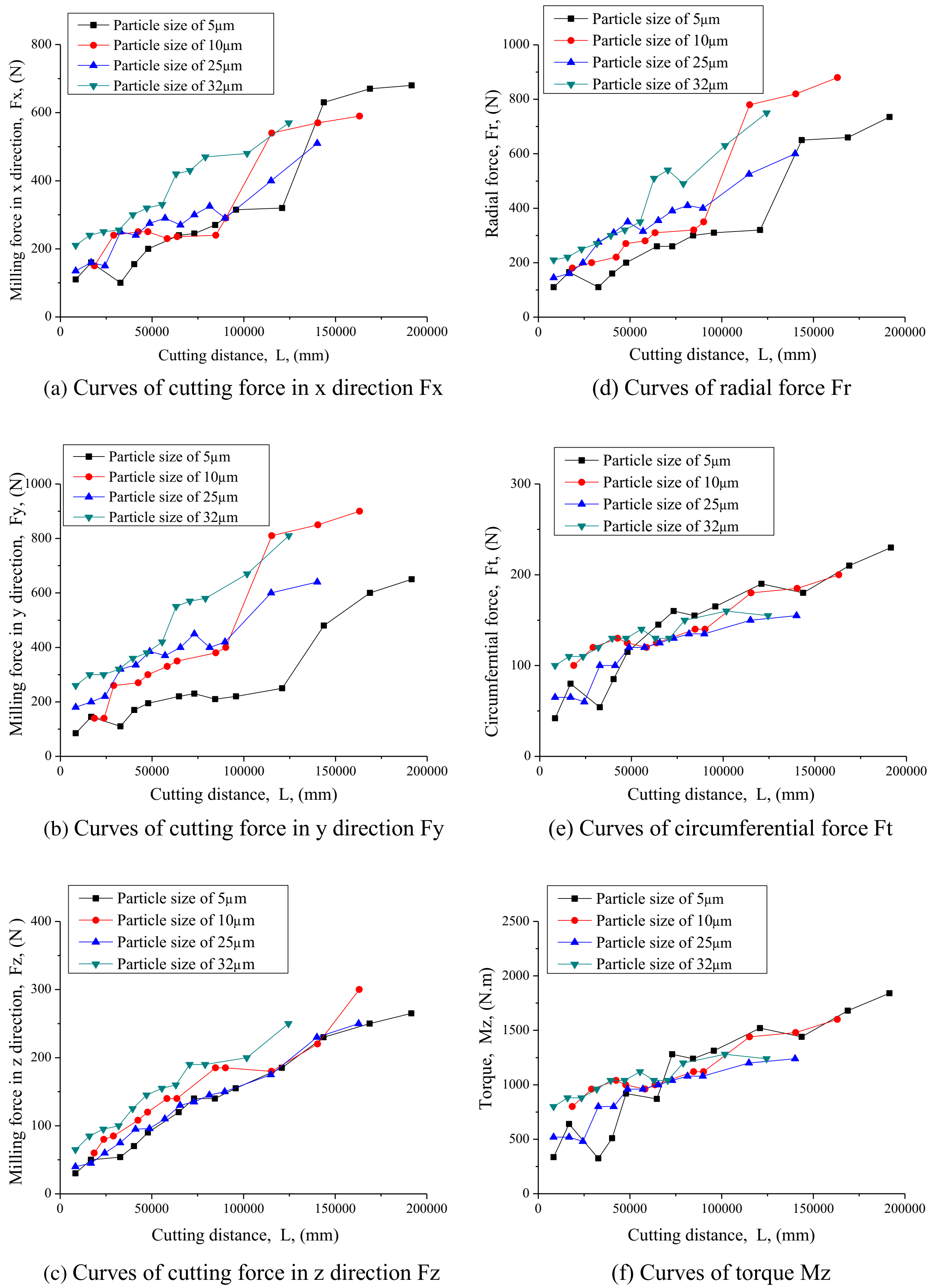
Figure 9 shows the transformation of wear morphology on rake face and flank face when the diamond particle size is 10 μm. In Fig. 9, the tool wear on rake face mainly appears as the pattern of local micro-chipping near the side cutting edge and the circular arc edge, when the cutting distance range from 0 to 163,177 mm. During the whole cutting process, the degree of the micro-chipping shows tiny improvement, but it is not obvious. The tool wear on flank face occurs on the corresponding zones near circular arc edge, and the wear amount VBmax increases with the increase of cutting distance. Besides, there is no obvious chipping and breakage, and the wear amount increases relatively uniformly in the whole cutting process. Compared with the four wear curves in Fig. 8, it can be seen that the wear rate in the initial cutting period is higher than that of the other stages. Then it increases smoothly when the cutter entering into the stable cutting period. Nevertheless, the tool wear rate improves obviously in the final cutting period. Specifically speaking, the tool wear amount increases 185 μm, when the cutting distance increases from 115,282 to 163,177 mm.

3.2 Effect of diamond particle size on cutting force

Under the condition of dry milling, SiCp/Al composites are machined by PCD tools with different particle size. The used cutting parameters are shown as described earlier. The direction of cutting force in high-speed milling of SiCp/Al composites with PCD tools is shown in Fig. 10.

The detailed variation tendency of cutting force which varies with cutting distance can be obtained in Fig. 11. And the values reflect the average of the maximum value of cutting force component in the whole cutting process.

It can be seen from Fig. 11 that the cutting force component Fx, Fy, Fz, Fr, Ft, and torque Mz all present curve upward trend with the addition of cutting distance. The values of Fz and Ft are both smaller and the increasing tendency is slower than other cutting force component. All in all, cutting force component is larger when the diamond particle size is larger. In the initial cutting period, the cutting force is larger relatively and shows linear increase tendency in the whole process when diamond particle size is 32 μm. But the cutting force component Fx, Fy, and Fr increase at a flat rate when particle sizes are 5 and 10 μm. The main reason is that the PCD tool is sharper in the initial cutting period, thus the value of cutting force is smaller. However, in the final cutting stage, the tool wear aggravates gradually with the addition of cutting distance, resulting in the raise of cutting force. So the cutting



(a) Curves of cutting force in x direction Fx

(d) Curves of radial force Fr

(b) Curves of cutting force in y direction Fy

(e) Curves of circumferential force Ft

(c) Curves of cutting force in z direction Fz

(f) Curves of torque Mz

Fig. 11 Milling force vs. cutting distance for PCD tools with different particle size

force component Fx, Fy, and Fr increase greatly when the cutting distance is beyond a certain value. There are two reasons for the phenomena as follows. On the one hand, the larger wear amount causes the increase of cutting force. On the other hand, tool wear causes the decrease of cutting depth resulting in hindering the addition of cutting force.

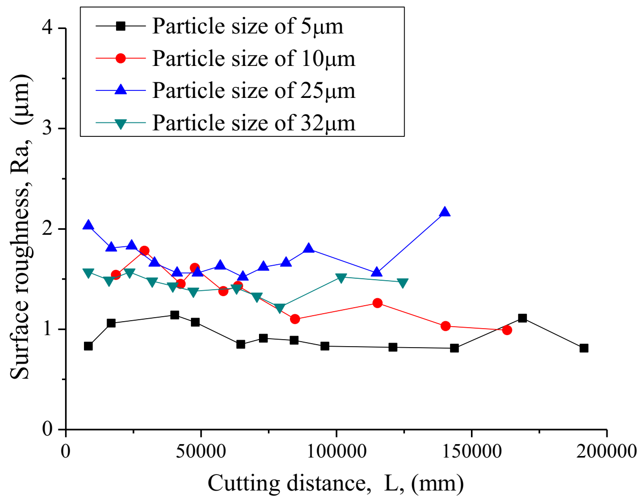


Fig. 12 Varying curves of surface roughness with the increase of cutting distance

3.3 Effect of diamond particle size on machined surface roughness

Figure 12 shows the varying curves of machined surface roughness with the increase of cutting distance, when PCD tools with different particle size are used in high-speed milling SiCp/Al composite materials. The roughness values are acquired by measuring values at five different positions on the machined surface of workpiece and then computing their average values.

As can be seen from Fig. 12, the machined surface roughness of workpiece fluctuates slightly with the increase of cutting distance. When diamond particle size is 5 μm, the surface roughness is smaller than that of other particle sizes in the whole cutting process. This is mainly because that the diamond particle size is small, and it is not easy to form micro-chipping on the cutting edge. Thereby, the flat cutting edge cannot scribe a deeper groove marks on the machined surface. However, when the diamond particle sizes are 10, 25, and 32 μm, respectively, the surface roughness does not show obvious corresponding relationship with diamond particle size of PCD tools. In general, there are two reasons leading to a slight growth trend of the surface roughness. On the one hand, it is easier to occur micro-chipping on the cutting edge when the diamond grain size is larger. Then the machined surface roughness also increases. On the other hand, the main method to remove SiC particles is micro-crushing and shedding in high-speed milling SiCp/Al composites.

4 Conclusions

PCD tools with different diamond particle size were used in high-speed milling SiCp/Al composites with volume fraction of 56% and SiC particles with an average size of 60 μm. Within the range of experimental conditions in this paper, the corresponding conclusions were acquired as follows.

1. The wear patterns of PCD tools with different particle size are mainly flank wear. There are no obvious wear marks on the cutting zone on rake face. However, there is micro-chipping phenomenon in different degrees on the cutting edge, and the degree has increased with the increase of diamond particle size.
2. There is a great influence of diamond particle size on wear resistance of PCD tools. The larger the size of diamond particle size is, the worse the wear resistance is. Under the experimental conditions adopted in the paper, the wear resistance of PCD tools with 5-μm particle size is the best, and that of 32-μm particle size is the worst. When the particle size is 32 μm, tool wear rate is higher in the initial cutting period, and the initial stage of severe wear is longer. When the diamond particle size of PCD tools is 5 μm, the wear rate is lower and the corresponding distance is shorter in the initial severe wear stage. However, when the tool wear go into a stable wear state, the wear rate of PCD tools with different particle size is almost the same.
3. In general, the cutting force is greater when the diamond particle size is larger. The cutting force increases with the addition of cutting distance, and the variation tendency keeps a better correspondence with tool wear.
4. The machined surface roughness fluctuates slightly with the increase of the cutting distance. And the value is also the smallest when the particle size is 5 μm.

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