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ORIGINAL ARTICLE

Effects of cooling and lubrication conditions on tool wear in turning of Al/SiCp composite

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Abstract
Al/SiCp composites machining is considerably difficult, owing to the presence of hard particles that result in severe tool wear. The application of different cooling and lubrication methods can offer a favorable change in the tool used in machining of Al/SiCp composites. To study the effects of different cooling and lubrication conditions on the tool wear in the machining of Al/SiCp composites, turning experiments under dry, liquid nitrogen (LN2), minimum quantity lubrication (MQL), cutting oil (Oil), and emulsion environments were conducted, and the mechanisms of tool wear with respect to boundary wear, major flank wear, adhesive wear, and tool breakage were discussed. The results indicate that the MQL and LN2, which exhibit excellent flushing performance, could wash away the chips and SiC particles from the boundary zones of the minor flanks, thus reducing the boundary wear. However, the use of Oil and emulsion promoted the formation of an abrasive slurry that enhanced the three-body abrasion at the boundary zones. In addition, the MQL and LN2, which show excellent lubricating and cooling properties, promoted the reduction of the major flank wear. The formation of worn pits and built up edge(s) (BUE) on the rake faces confirmed the presence of adhesive wear in the turning of the Al/SiCp composite using polycrystalline diamond (PCD) tools, and the cooling effect of MQL and LN2 could not prevent the workpiece material from accumulating in the worn pits and giving rise to the BUE. When turning Al/SiCp composites under LN2 and Oil conditions, the tool breakage was accelerated. The application of LN2 increased the thermal impact and the scratch effect of the SiC particles on the tool faces, aggravating the tool breakage. The rapid tool breakage caused by Oil cutting could be attributed to the reduction of the cutting edge strength that bore the alternating load and thermal impact. Therefore, it is concluded that the use of MQL, which assists in reducing the boundary wear, tool breakage, and major flank wear, is suitable as the preferred cooling and lubrication mode in the turning of Al/SiCp composites.

Keywords Al/SiCp composites · Cooling and lubrication · Tool wear · Boundary wear · Tool breakage · Adhesive wear · Major flank wear

1 Introduction

A need for lightweight and high-strength materials in advanced weapon systems, aerospace, electronic packaging, and other industrial fields grows with the development of technologically advanced industries [1, 2]. Composite materials, known as the "materials of the future" in the 1970s, play an important role in the development of lightweight and high-strength materials. Among modern composite materials, the silicon carbide particle-reinforced aluminum matrix composite (Al/SiCp composite) has excellent comprehensive properties, such as high specific strength, high specific stiffness, high wear resistance, corrosion resistance, and a light weight [3, 4]. However, Al/SiCp composites machining is very difficult owing to its heterogeneity, and the reinforcements are extremely abrasive, resulting in severe tool wear [5–8]. The hardness of SiC particles in an Al/SiCp composite is close to that of many cutting tool materials and higher than that of an Al matrix, and thus their abrasive nature increases the cutting tool wear and severely affects the quality and integrity of the machined surface [9].

Cooling and lubricating liquids are widely used in cutting operations, and significantly influence the tool life,

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dimensional accuracy, and surface quality of the machined parts [10, 11]. Some studies showed that the tool wear in Al/SiCp composites machining was influenced by different cooling and lubricating conditions. Sankar et al. [12] developed and applied a minimum quantity cutting fluid (MQCF) technology for enhancing the machining performance and maintaining eco-friendly conditions. They conducted a series of machining experiments on Al/SiCp composite using cemented carbide tools under MQCF and flood cooling and concluded that the MQCF reduced the forces, surface roughness, and flank wear by 17%, 5%, and 12.5%, respectively, as compared to flood cooling. Sadik et al. [13] studied the influence of the coolant and cooling strategy on the machinability of Al/SiCp composites with respect to tool life and wear development in the drilling process. The results showed that drilling with an internal supply of CO_2 significantly reduced the tool wear as compared to the other cooling strategies. Ding et al. [6] conducted turning experiments to study the performance of various cutting tools during Al/SiCp composite machining, and reported that the using coolant resulted in an increase in notch wear on the flank faces of the cutting tools, and a deterioration of the surface finish. A study from Kannan et al. [14] showed that the influence of coolant on flank tool wear was more significant at higher cutting speeds than at lower cutting speeds in Al/SiCp composite machining. They attributed this phenomenon to the lack of formation of a lubricating layer/film at higher cutting speeds. The previous studies [15–17] presented improvements in various aspects of cutting machinability, either by cryogenically freezing the workpiece, or by spraying LN2 to the general cutting area. In addition, LN2 is safe for the environment, and requires no disposal facilities. Thus, the use of LN2 has great potential for improving tool life, and can realize an environmentally friendly manufacture in the machining of Al/SiCp composite.

The studies mentioned in the previous section on tool wear in Al/SiCp composite machining were primarily focused on the flank wear. However, owing to the existence of harder particles as a reinforcement in the matrix, the Al/SiCp composite machining can produce more complex tool wear, including serious flank wear, adhesive wear, and rapid tool breakage. The flank wear promotes the adhesion of the workpiece material because of the high pressure and temperature between the flank face and workpiece. The adhesive wear further reduces the quality and integrity of the machined surface [18, 19]. The tool breakage caused by high-frequency abrading and hitting from the SiC particles against the tool surface increases the manufacturing cost of the parts [5, 20]. Therefore, to provide a more comprehensive understanding of the mechanism of tool wear in Al/SiCp composite machining, in addition to the flank wear, the tool breakage and adhesive wear should also be studied in detail.

Coolant is utilized during the cutting process to reduce the thermal load of the cutting edge and the flank wear of the cutting tool [21]. However, owing to the abrasive reinforcements mixed with the matrix, the effects of the abrasive particles on the tool wear become more prominent than those of the thermal load in Al/SiCp composite machining [6]. Lubricating fluid can build the protective and lubricating layers at the tool-chip and tool-workpiece interfaces to reduce the friction, and it can also flush away the particles to result in lower abrasive wear [1, 14]. Therefore, to comprehensively analyze the influence of cutting fluid on the tool wear in Al/SiCp composite machining, in addition to the cooling, the effects of the lubrication and flushing in the cutting zone should also be examined. However, most investigations only showed the effect of cooling on the tool wear when machining an Al/SiCp composite [1, 6, 12, 22]. The mechanism of tool wear during Al/SiCp composite machining under different cooling and lubrication conditions has not been sufficiently explored, but it is required to improve the machining performance of the Al/SiCp composite.

This paper presents the findings of experimental investigations into the effects of cooling and lubrication conditions on tool wear during the turning of Al/SiCp composite. The contributions of this research are as follows: (1) the cooling and lubrication environments of Al/SiCp composite turning comprehensively consider MQL, LN2, Oil, and emulsion conditions; and (2) the complex tool wear mechanism during turning of Al/SiCp composite under different cooling and lubrication environments is revealed from the flank wear (including the boundary wear of major and minor flanks), adhesive wear, and tool breakage.

2 Experimental procedures

The turning experiments were performed on a CA6140 lathe, using cylinder workpieces under different cooling and lubrication conditions. 2024Al was used as the matrix material, and SiC particles of 50 vol% with an average size of 15 μm were used as the reinforcement. To verify the Al/SiCp composite with 50 vol% of SiC, microstructure photographs of Al/SiCp composite at different cross-sections were taken for image processing. The microstructure photograph was binarized, so that the photograph appeared in black and white, as shown in Fig. 1 b. Subsequently, the ratio of the area of the black area to the entire area of the photograph was calculated. The average value of the area ratios at different cross-sections of Al/SiCp composite is 52.38%. This verifies that the volume fraction of SiC particles approximates 50%. The 2024 aluminum alloy contains 0.5% SiC, 3.8~4.9% Cu, 1.2~1.8% Mg, 0.25% Zn, 0.15% Ti, and balance Al. Figure 1 a shows the microstructure of the Al/SiCp composite, as manufactured by a stir casting process. To purify the pores and inclusions in the molten aluminum alloy, the molten aluminum alloy was filtered using a ceramic filter before the molten aluminum

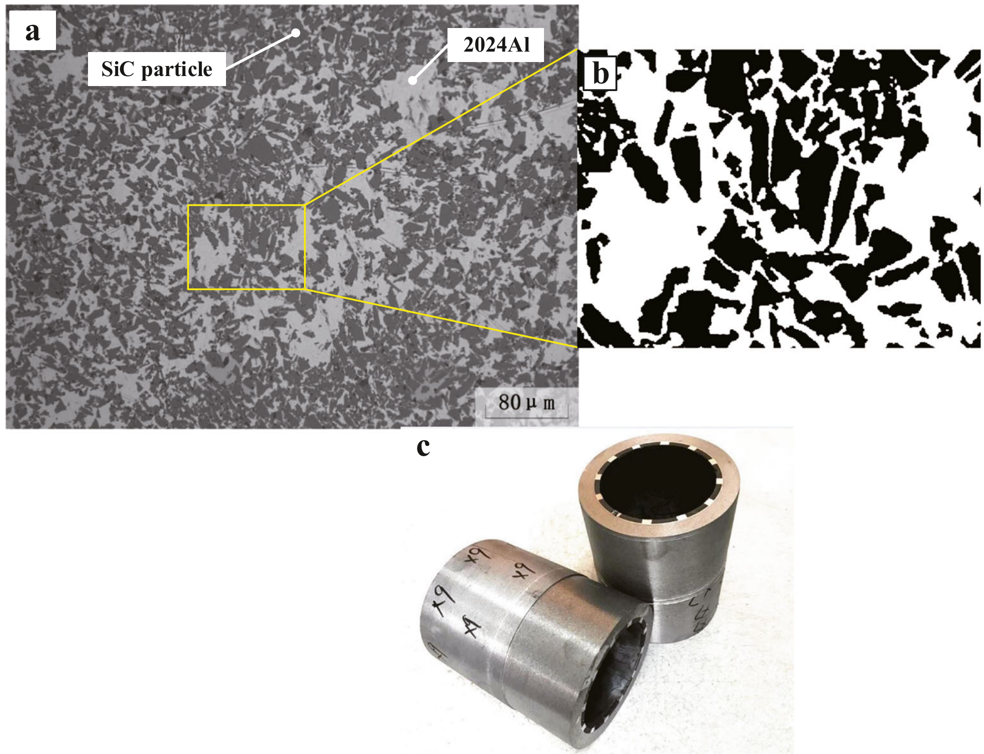

Fig. 1 Experimental material. **a** Microstructure of the Al/SiCp composite, **b** the image binarization corresponding to **a**, and **c** the shape of Al/SiCp composite workpieces

alloy was poured. On the other hand, before the stir casting of Al/SiCp composite, the SiC particles were preheated at high temperature for a certain period of time to absorb gases from the SiC surface. The physical and mechanical properties of the Al/SiCp composite are listed in Table 1. The external diameter, internal diameter, and length of the cylindrical workpiece are 120 mm, 100 mm, and 150 mm, respectively, as shown in Fig. 1 c. These cylindrical workpieces were directly obtained by casting.

The previous studies demonstrated that the PCD diamond tool is most preferred cutting tool in Al/SiCp composite machining [1, 2]. Thus, a PCD tool insert was selected as the turning tool, with a principal cutting edge angle (k_r) of 90°, rake angle (γ_o) of 5°, relief angle (α_o) of 7°, and tool edge radius of 0.4 mm. To minimize the influence of tool wear on the investigated quantities, a new PCD insert was used for each cooling and lubrication method. To guarantee better machined surface quality and achieve longer tool life in the turning of Al/SiCp composite, the cutting speed, cutting depth, and feed rate were set as 120 m/min, 0.2 mm and 0.1 mm/rev, respectively. To obtain the morphology of tool wear, the used cutting tools were cleaned in 10 wt% NaOH solution to remove adhesion materials. The micromorphology of tool wear was observed by a FEI (Q45) scanning electron microscope (SEM). The chemical composition of the rake faces was analyzed by energy dispersive spectrometry (EDS). The flank wear that includes boundary wear of major and minor flanks near the tool nose was measured using a VTM-3020F tool microscope at each 137.5 m of cutting distance. The total cutting distance of each cooling and lubrication condition was 1375 m. All tests were repeated at least two times. The cooling and lubrication conditions used in turning experiments are as follows:

I. Dry: no cooling and lubricating substances were used in the cutting process.
II. Oil: HOUGHTON MACRON 400 M-22 was added, but we did not add water to dilute it when cutting. Its kinematic viscosity was 22 mm^2/s, and the amount of fluid supply was 36 L/h.

Table 1 The physical and mechanical properties of Al/SiCp composite

Material	Density (kg/m^3)	Yield strength (MPa)	Compressive strength (MPa)	Elastic modulus (GPa)
Al/SiCp composite	2915	395	425	80.1

III. Emulsion: HOUGHTON HOCUT 5759 AL-S was added, the mixing ratio of oil and water was 1:10, and the amount of fluid supply was 36 L/h.

IV. MQL: minimum quantity lubrication (MQL) is formed by mixing oil and gas with a certain pressure. The oil used in MQL is the lubricant. Thus, the lubricant name is HOUGHTON MACRON 400 M-22. The mixing pressure of oil and gas was 0.4 MPa. The diameter of the nozzle was 2 mm. The distance between the nozzle and cutting zone was 10 cm, and the oil consumption was 83 ml/h.

V. LN2: a self-pressurized LN2 tank with a 165 L effective volume was used for liquid supply. The experimental fluid supply pressure was 0.4 MPa, and the diameter of the nozzle was 2 mm. The distance between the nozzle and cutting zone was 10 cm, and the calibration temperature of the corresponding target distance was − 165 °C (room temperature is 25 °C).

Figure 2 shows the schematic of tool wear in turning of Al/SiCp composite. Because the tool edge radius is larger than the cut depth in turning of Al/SiCp composite, the tool nose is mainly responsible for the removal of Al/SiCp composite, as shown in Fig. 2 a. However, the violent impact on the tool nose leads to the flank wear concentrated on the boundary zone of the minor flank and the tool nose zone of the major flank. Simultaneously, no obvious uniform wear zone appears in the middle part of the major flank. Thus, *VN* (the width of boundary wear at the minor flank) and *VC* (the maximum width of the wear zone of the major flank near the tool nose) under different cooling and lubrication conditions were observed and recorded as the wear parameters to evaluate the flank wear in the turning of Al/SiCp composite, as shown in Fig. 2 b. To study the adhesive wear, the height of the BUE H_b under different cooling and lubrication conditions was recorded, as shown in Fig. 2 c.

3 Results and discussion

3.1 Boundary wear of minor flank

During the cutting of Al/SiCp composite, the reinforced particles acted as an abrasive between the tool flank and the workpiece, which caused high flank wear [23–25]. The worn flank promoted the softening matrix to adhere to the tool surface owing to the high pressure at the tool-workpiece interface [1]. This further reduced the quality and integrity of the machined surface [18, 19]. Therefore, the study of flank wear is essential to improve the quality and integrity of the machined surface. The effects of cooling and lubrication conditions on the boundary wear of the minor flank are discussed in the following sections.

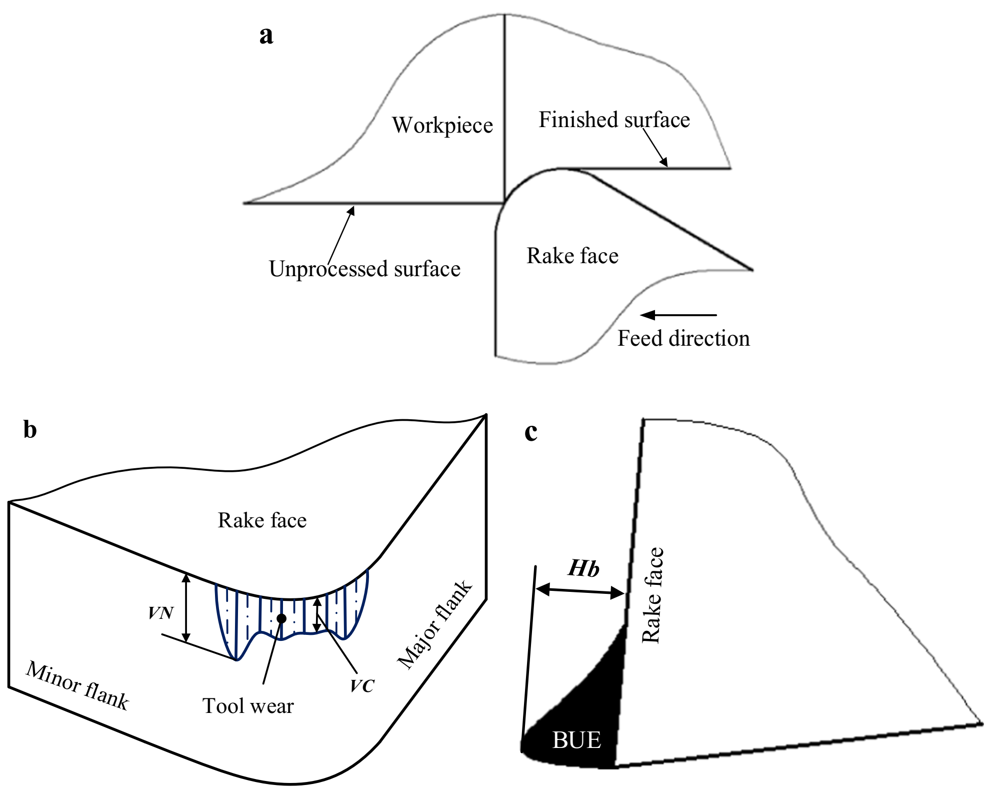

Fig. 2 Schematic of flank wear in turning of Al/SiCp composite. **a** The schematic diagram of the turning experiment, **b** the geometry of flank wear, and **c** the schematic of the BUE

3.1.1 Formation mechanism of boundary wear

To remove the adhesion materials and obtain the wear morphology at the boundary zones of the minor flanks, the PCD inserts used under different cooling and lubrication conditions were etched and observed when the total cutting distance reached 1375 m. The SEM images of the boundary wear patterns of the minor flanks after Al/SiCp composite turning under dry, MQL, LN2, Oil, and emulsion conditions are shown in Fig. 3. As shown in Fig. 3 a, d, and f, during the turning of Al/SiCp composite under dry, oil, and emulsion conditions, the abrasive notches appear in the boundary zones of the minor flanks. However, under MQL and LN2, the boundary wears of the minor flanks are reduced, as shown in Fig. 3 b and c. In addition, from Fig. 3 e, severe groove wear is formed in the boundary zone of the major flank during turning of Al/SiCp composite under the Oil environment. Under the LN2 cooling environment, severe tool breakage is observed at the minor cutting edge, as shown in Fig. 3 c.

The two-body abrasion can be formed by abrading between the softer surface and hard surface, and the three-body abrasion is caused by hard particle rolling between two sliding surfaces [9]. Figure 4 shows the wear morphology of the PCD tool inserts when the total cutting distance reached 412.5 m in Al/SiCp composite turning under the dry environment. As shown in Fig. 4, the grooves parallel to the direction of chip flow and workpiece material movement indicate that the two-body abrasive wear occurred. According to the study of Fang et al. [26], the three-body abrasion could create scratches at a low wear rate or the craters at a high wear rate. The scratches and craters on the wear surface of the rake face and flank as shown in Fig. 4 confirm the occurrence of three-body abrasion. To provide an insight into understanding the boundary wear in turning of Al/SiCp composite, the process of boundary wear at the minor flank was modeled, as shown in Fig. 5. At the initial stage, the contact area between the new cutting edge and workpiece is small, as shown in Fig. 5 a. At this stage, the hard SiC particles abraded and hit the tool surface with high frequency, which is a dominant wear mode, and resulted in microchipping in the tool nose as shown in Fig. 4 b. As the cutting distance increased, the microchipping expanded on the cutting edge and the contact area at the tool-workpiece interface increased, as shown in Fig. 5 b. Then, owing to the increase of the contact area between the tool and workpiece, more hard particles abraded the tool surface by two-body sliding and three-body rolling. Thus, the dominant wear mode became two-body and three-body abrasive wears, and grooves, scratches, and craters were produced in the tool surface, as shown in Fig. 4 b. The SiC particles constrained in the workpiece abraded the PCD insert surface, leading to the two-body abrasion. A proportion of debonded SiC particles rolled between the tool and workpiece surface as

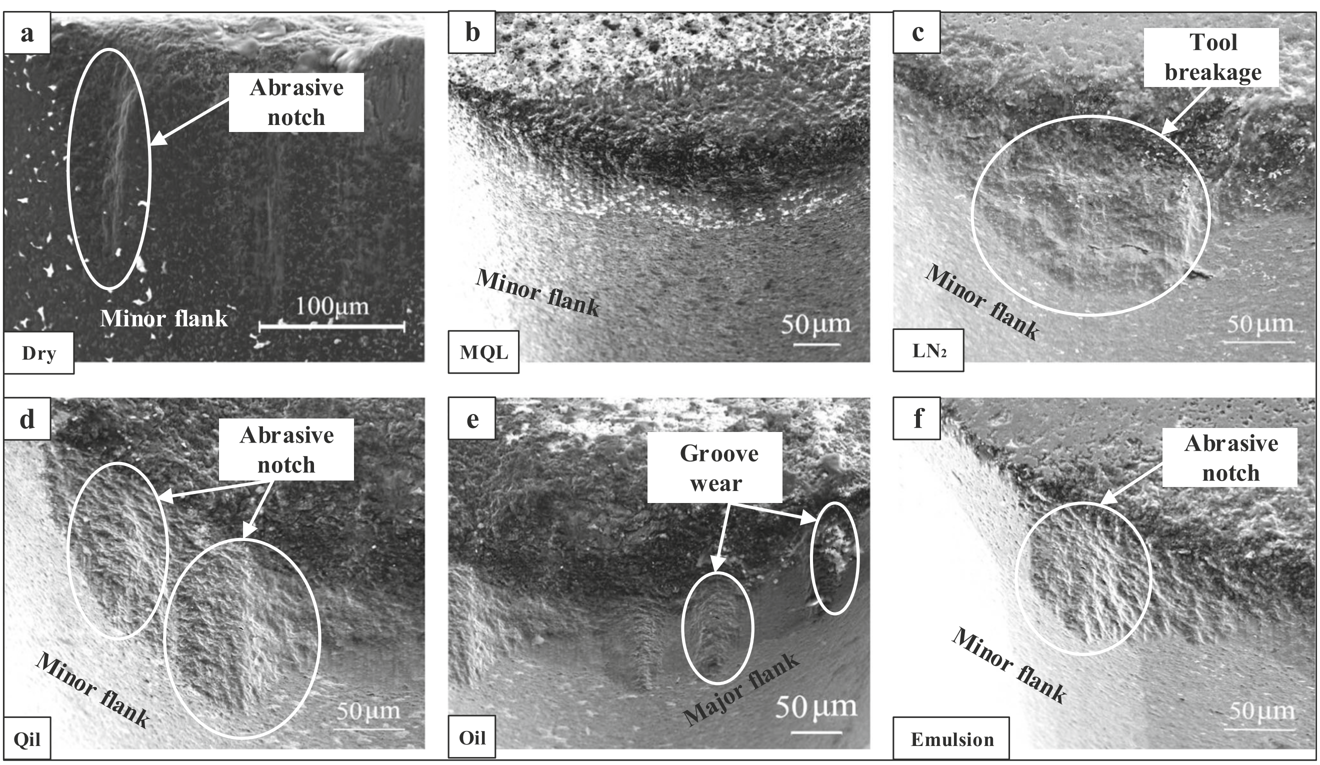

Fig. 3 **a**–**f** SEM images of the boundary wear patterns of the minor flank of the PCD inserts when the total cutting distance reached 1375 m in Al/SiCp composite turning, under dry, MQL, LN2, Oil, and emulsion conditions

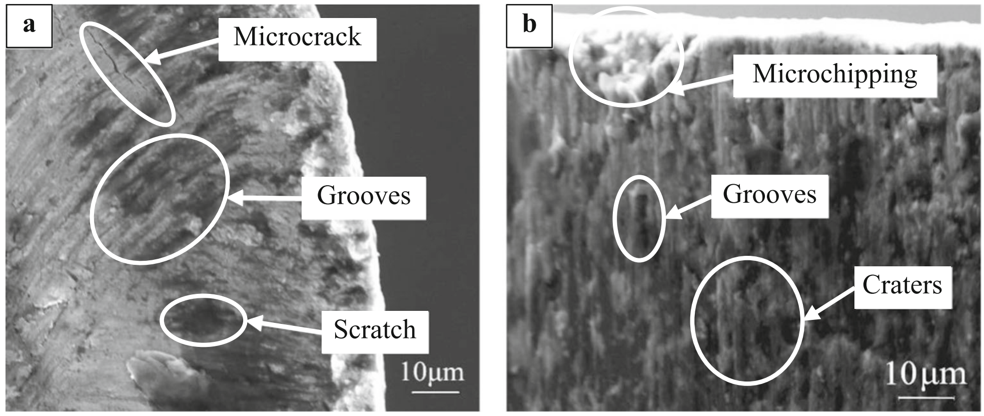

Fig. 4 SEM images of the wear morphology of the PCD tool inserts when the total cutting distance reached 412.5 m in Al/SiCp composite turning under the dry environment. **a** The rake face and **b** the minor flank

shown in Fig. 5 b, leading to the three-body abrasion. Therefore, the abrasive wear, which includes the two-body and three-body abrasions, is regarded as the mechanism determining the boundary wear during the turning of Al/SiCp composite.

According to the above analysis, two ways are advised to reduce the boundary wear of the minor flank in Al/SiCp composite turning:

(1) Producing lubrication layer. The effective lubrication layers formed by lubricating fluid can reduce the actual contact area at the tool-workpiece interface, resulting in the reduction of two-body abrasion.
(2) Reducing the number of rolling SiC particles. The three-body abrasion can decrease with a decrease in the number of rolling particles between the tool and workpiece. Under certain cooling and lubrication conditions, the cutting fluid can flush out a proportion of rolling particles in the cutting zone to reduce the three-body abrasion.

3.1.2 Effects of cooling and lubrication conditions on boundary wear

Figure 6 shows the growth of the boundary wear at the minor flanks, *VN* with cutting distance during Al/SiCp composite turning under dry, MQL, LN2, Oil, and emulsion conditions. From Fig. 6, the LN2 and MQL used in Al/SiCp composite turning helped to reduce the boundary wear of the minor flank as compared to dry turning. However, the use of Oil and emulsion resulted in a significant increase in the boundary wear. The Oil and emulsion supplied by pouring fluid into the cutting zone restricted the SiC particles and chips to be flushed out from the tool-workpiece interface. Moreover, the volume fraction of particles in the experiment material is high, and the chips and debonded particles were mixed with the cutting fluid and gathered around the cutting zone to form an abrasive slurry containing the SiC particles, as shown in Fig. 7 a and b. Meanwhile, the mixing of cutting fluid with SiC particles increases the viscosity of the abrasive slurry, which makes it easier for the particles to stay in the cutting zone. Obviously, the retention of SiC particles caused by the abrasive slurry in the cutting zone led to severe three-body abrasive wear. Although Oil and emulsion have excellent lubrication properties, the lubricating condition did not show a remarkable effect on reducing the boundary wear. This can be attributed to the formation of the abrasive slurry. During turning of Al/SiCp composite under Oil and emulsion conditions, the effect of the abrasive slurry on the tool wear is more prominent than that of the lubricating fluid, leading to an increase in the boundary wear. Compared with the emulsion, the Oil without diluting increased the kinematic viscosity in the abrasive slurry. The thicker abrasive slurry resulted in a larger number of SiC particles that gathered around the cutting zone and caused the enhancement of the three-body abrasion. Therefore, the Al/SiCp composite turning under the Oil

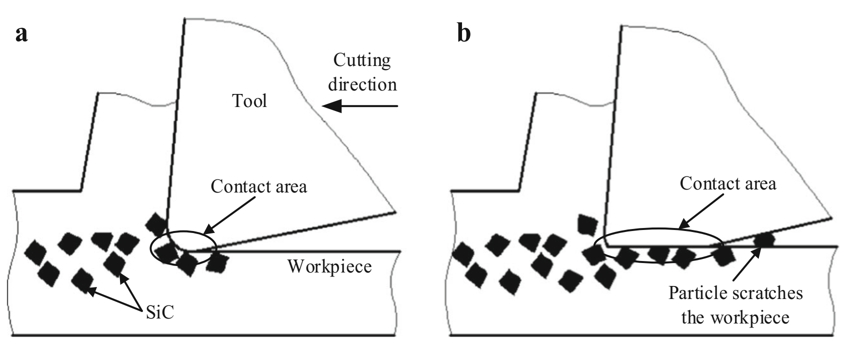

Fig. 5 **a**, **b** Wear process of boundary zone of minor flank in Al/SiCp composite turning

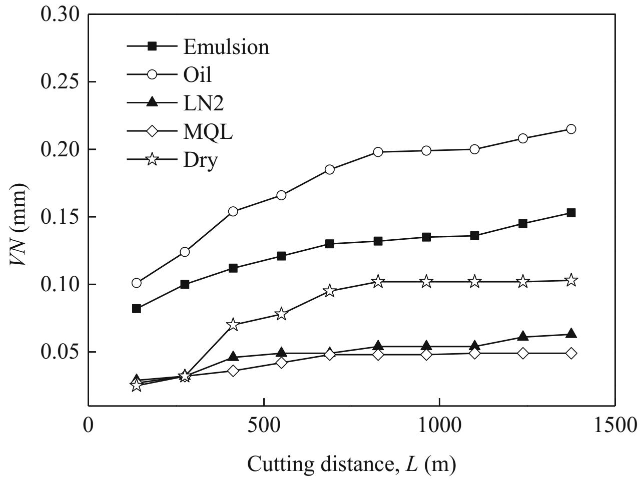

Fig. 6 Variation of boundary wear with cutting distance in turning of Al/SiCp composite under dry, MQL, LN2, Oil, and emulsion conditions

environment led to a faster boundary wear as compared to emulsion. A study showed that using coolant that led to a more difficult shear of workpiece material could cause an increase in the severity of abrasion between the flank face and the machined surface and exacerbate the tool wear [6]. However, the Al/SiCp composite turning under emulsion has a better cooling effect on tool wear than that of the Oil, but results in the reduction in the boundary wear. Therefore, in the turning process of Al/SiCp composite, the effect of cooling is not the dominant factor for determining the boundary wear. As stated above, during the Al/SiCp composite turning under emulsion and Oil conditions, the boundary wear of the cutting tool was dominated by the abrasive slurry that was formed by mixing of SiC particles and cutting fluid.

The flushing effects of different cooling and lubrication conditions on the PCD tools in SiCp/Al composite cutting are shown in Fig. 7. As compared with Oil and emulsion, the MQL and LN2 supplied by pressure injection significantly improved the flushing effect of the cutting fluid. During the Al/SiCp composite cutting under MQL and LN2, the chips and debonded particles could be rapidly washed away from the cutting zone by the pressurized fluid, and the retention of chips and SiC particles was reduced. This prevented the formation of the abrasive slurry and reduced the three-body abrasion, as shown in Fig. 7 c and d. Consequently, the boundary wear under MQL and LN2 conditions was significantly lower than that obtained under Oil and emulsion conditions. The application of MQL and LN2 played the role of the second method to reduce the boundary wear of the minor flank proposed in Section 3.1.1. Furthermore, for MQL cutting, it was easier for the pressurized and atomized micro-lubricating fluid to enter the contact area of the tool face and the machined surface, and then the lubricating layer was produced, which reduced the actual contact area at the tool-workpiece interface. The minor flanks were protected by the lubricating layers against further abrasion. The application of MQL provided excellent lubrication performance, and further limited the formation of the abrasive slurry. Therefore, the boundary wear

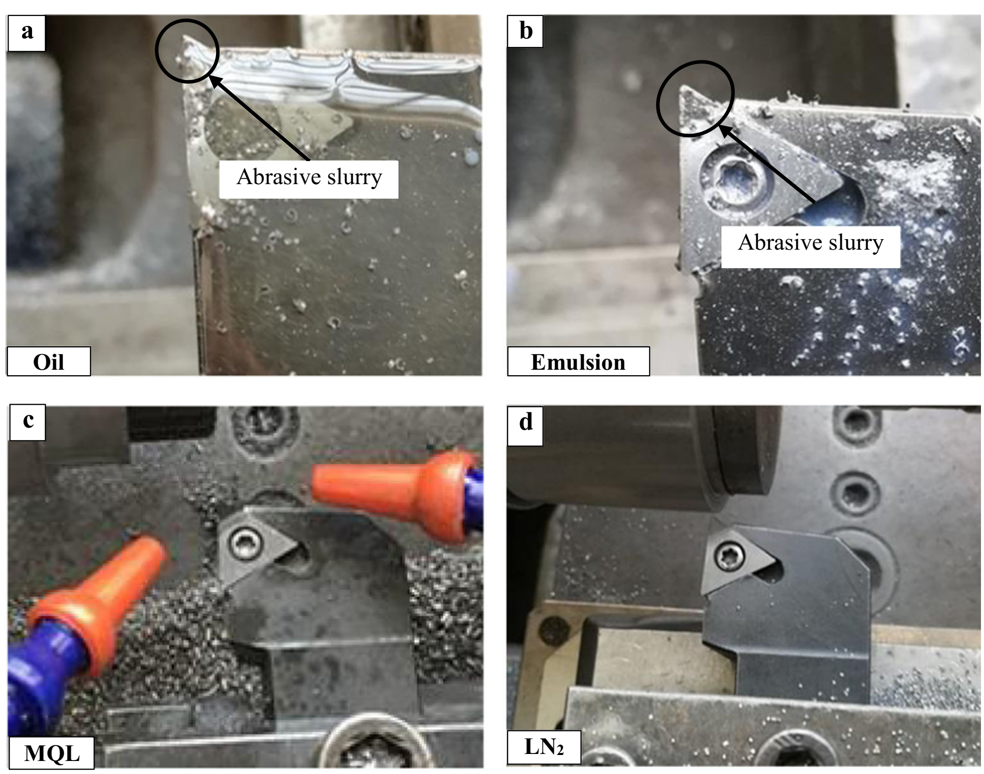

Fig. 7 **a**–**d** Flushing effects on the tools in turning of Al/SiCp composite under MQL, LN2, Oil, and emulsion conditions

VN under the MQL condition shows the minimum value, as shown in Fig. 6. The use of LN2 with excellent cooling performance, which reduced the thermal softening tendency of the machined surface, resulted in an increase in the strength and hardness of the workpiece, and finally, the tool wear should have been increased. Nevertheless, the boundary wear *VN* under LN2 condition maintained a relatively low value that is close to the *VN* value of MQL, as shown Fig. 6. This phenomenon may be attributed to two points. First, because the supplied pressure is the same (0.4 MPa), the flushing performance of LN2 is close to that of MQL that reduced the three-body abrasive wear. Second, the cooling of LN2 could effectively maintain the hardness of the PCD insert, and therefore, the wear resistance of the tool was increased. The foregoing analysis indicates that in the turning process of Al/SiCp composite under different cooling and lubrication conditions, the performances of cooling and lubrication cannot significantly affect the boundary wear, but the effect of flushing becomes a dominant factor for determining the boundary wear.

3.2 Major flank wear

The wear acceleration at the major flanks can result in a rapid tool breakage that aggravates the tool failure. Therefore, a detail investigation of major flank wear is needed for the improvement of tool life in machining of Al/SiCp composites. Because the wear zone at the major flank frequently appears near the tool nose in the turning process of Al/SiCp composites, the investigation into major flank wear should concentrate on the tool nose region.

Figure 8 shows the variation of the major flank wear, *VC*, with cutting length during the Al/SiCp composite turning under dry, MQL, LN2, Oil, and emulsion conditions. From the figure, in the Al/SiCp composite turning under LN2 and MQL, the major flank wear is lower as compared with other cutting fluids. In addition, comparing Fig. 6 and Fig. 8, the difference of *VC* values between the different cooling and lubrication conditions is decreased as compared with *VN* values. The major flank face near the tool nose bore the high pressure from the machined surface, which limited the number of three-body rolling particles at the tool-workpiece interface. This indicates that the three-body abrasion is not the main mechanism determining the major flank wear during the turning of Al/SiCp composite. Therefore, the flushing of the cutting fluids offered no significant influence to the major flank wear, leading to the decrease in the difference of *VC* values between the different cooling and lubrication conditions. With the decrease in the effect of three-body rolling on the major flank wear, two-body abrasion became the dominant mechanism in determining the major flank wear in the cutting of Al/SiCp composite.

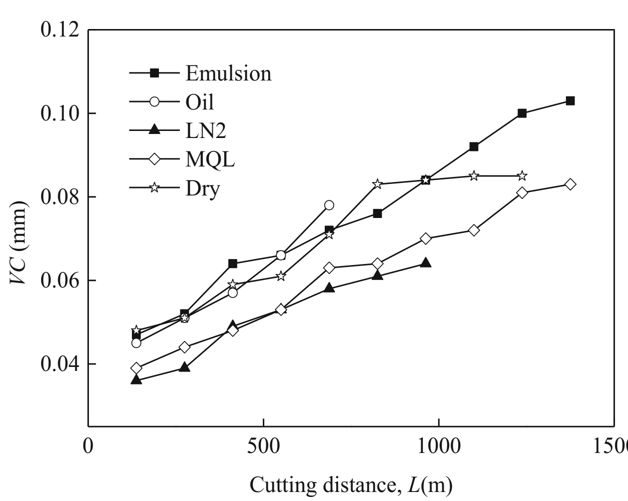

Fig. 8 Variation of major flank wear with cutting distance in cutting of Al/SiCp composite under dry, MQL, LN2, Oil, and emulsion conditions

The major flank near the tool nose endured high temperatures because of the poor heat dissipation capacity in the cutting zone. Owing to the rising cutting temperature near the tool nose, the cutting fluid entering the cutting zone formed a steam film between the major flank and machined surface, which prevented the fluid from entering the cutting zone and weakened the convection heat transfer intensity and the effects of cooling and lubrication on major flank wear. Therefore, the Oil and emulsion, with general cooling and lubrication properties, did not show a remarkable effect on reducing the major flank wear as compared to dry cutting, as shown in Fig. 8. However, for MQL cutting, the pressurized atomizing microlubricating fluid was sprayed out in the form of mist, and then the lubricating fluid with high-pressure broke through the steam film and produced a lubricating layer at the tool-chip and tool-workpiece interfaces. The lubricating layer reduced the actual contact area in the cutting zone, and consequently reduced the probability of SiC particles abrading the PCD insert. Additionally, LN2, with its excellent cooling performance, reduced the cutting temperature and limited the formation of steam film. Subsequently, the water vapor that condensed on the workpiece surface at low temperature infiltrated the cutting zone and improved the lubricating property in machining of Al/SiCp composite under the LN2 environment. Simultaneously, the cooling of LN2 effectively maintained the hardness of the PCD insert, thereby enhancing the wear resistance of the tool. Therefore, MQL with its excellent lubricating property and LN2 with its exceptional cooling performance promoted a reduction in the major flank wear during the cutting of Al/SiCp composite.

3.3 Adhesive wear

Adhesive wear frequently occurs when two smooth surfaces slide over each other. Owing to the relative movement between the tool face and machined surface, fragments are removed from the machined surface and adhere to the tool face, and then these fragments detach from the tool face and either get transferred back to the machined surface or form loose wear particles [19, 27]. The fragments removed from the tool faces can drag out the tool material, causing the adhesive wear. The adhesive wear gives rise to the formation of a BUE that has a significant effect on the cutting force, cutting temperature, surface roughness, and geometric dimensions of machined products [28, 29]. Therefore, adhesive wear is an important research subject for improving the tool performance. The adhesive wear mechanism and the effect of cooling and lubrication conditions on adhesive wear in machining of Al/SiCp composite are discussed in the following section.

3.3.1 Formation of adhesive wear

The workpiece material that adheres constantly to the rake face can produce the BUE. Formation of the BUE is a cyclic-dynamic process, including the initiation of the BUE at the rake face, the growth of the BUE to a certain size with irregular shape and geometry, and the BUE debonding from the rake face. With the continuous growth and breaking of the sticking material and BUE, the material of the rake face were removed gradually by those adhesive materials until severe adhesive wear was caused on the rake face [20, 28]. For adhesive wear, one major influencing factor is temperature [18]. During turning of the workpiece, the plastic deformation and friction induced a temperature increase in the contact zone between the rake face and the chip internal face. The adhesion was predominantly generated in the areas of local stress peaks with the highest temperatures [18]. Another significant influence on adhesive wear is the tool property [1]. For instance, owing to the higher hardness of the diamond tools and the lower chemical affinity with the MMC material, the PCD tool used in turning of the low content composite presented better wear resistance and produced a lower propensity for workpiece material adhesion [6, 30–32]. However, during the machining of Al/SiCp composite reinforced with a high content of SiC particle exceeding 40 vol%, the enhancement of the effect of particles on the rake face increased the tendency for workpiece material to adhere to the diamond tools. The large number of hard particles causes severe abrasive wear, resulting in the formation of worn pits and grooves on the tool face. In contrast, the worn pits and grooves on the tool face increase the adhesion property of the PCD tool. Figure 9 a and b show the wear morphology of the rake face in dry turning of Al/SiCp composite. In the Fig. 9 a, a BUE is found. After the PCD insert shown in Fig. 9 a is etched, many worn pits and grooves appear on the rake face, as shown in Fig. 9 b. To study the formation mechanism of the pits and grooves on the rake face, the EDS spectrums on the rake face are shown in Fig. 9 c and d. Compared to the unused PCD tool, the worn pits on the rake face of the tool used under dry conditions contain a large number of Si and Al elements from the workpiece material (Al/SiCp composite). This confirms the presence of atomic adsorption between the rake face and workpiece in cutting Al/SiCp composite, and verifies that the workpiece material is strongly bonded to the rake face. During the cutting of Al/SiCp composite with a high-volume fraction of SiC particles, the high-frequency hard particles abraded and hit the tool surface, and the bond strength between the PCD grains was reduced, resulting in the grains falling off from the rake faces of PCD tools, thereby producing the worn pits and grooves. These worn pits and grooves increased the adhesion property of diamond tools and afforded the Al/SiCp composite a

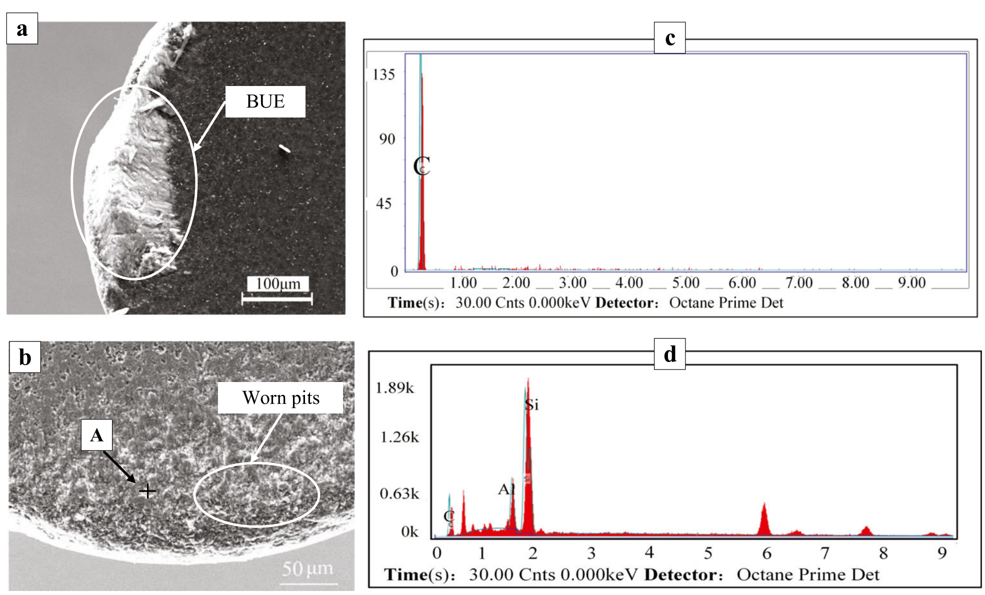

Fig. 9 Adhesive wear morphology and energy dispersive spectrometry on the rake face in turning of Al/SiCp composite under dry condition. **a** The morphology of the rake face before etching and **b** the morphology of the rake face after etching. **c** The chemical composition in the rake face of the unused PCD insert and **d** the chemical composition of location A

greater tendency to adhere to the tool face. Therefore, several Si and Al elements from the workpiece material were found in the pits and grooves. This phenomenon confirms that the workpiece material adhered to the tool face. When the adhesive material thickness increased to a certain value, a visibly thick BUE appeared on the tool surface, as shown in Fig. 9 a. The BUE as a protective film between the tool and chips also indicates that adhesive wear was formed on the PCD tool surface.

Based on the foregoing analysis, the appearance of BUE and worn pits confirmed that adhesive wear was developed on the PCD tools. In addition, a larger number of worn pits and grooves were produced on the rake faces owing to the reduction of bond strength between the PCD grains, thereby generating a greater tendency to adhere to the tool face during the turning of Al/SiCp composite with a high particle content.

3.3.2 Effects of cooling and lubrication conditions on adhesive wear

Figure 10 a shows the wear morphology of the rake face before etching. A visible BUE is shown on the rake face under LN2 cutting in Fig. 10 a-LN2, and the adhesive material is found on the rake face under MQL and Oil cutting. In fact, the application of MQL also formed the BUE during turning of Al/SiCp composite, but the BUE fell off from the rake face when the cutting distance reached 1375 m, and thus, only a small amount of material attached to the rake face under MQL cutting, as shown in Fig. 10 a-MQL. Although the use of Oil gave rise to rapid tool breakage, almost no workpiece material was attached to the rake face before the tool breakage. After the tool breakage, the adhesive material was presented on the rake face under the Oil cutting, but the BUE was not produced, as shown in Fig. 10 a-Oil. In addition, during Al/SiCp composite turning under the emulsion environment, a significant adhesion was not formed on the rake face throughout the cutting process, as shown in Fig. 10 a-emulsion. Figure 10 b shows the wear morphology of the rake face after etching. The worn pits on the rake face under different cooling and lubrication conditions observed in this figure are the consequence of the adhesive wear. Figure 11 shows the variation of BUE height in the turning of Al/SiCp composite under dry, MQL, and LN2 conditions. The height values of BUE under dry, MQL, and LN2 conditions follow a periodic variation with a similar trend. This is because that the formation of BUE in the cutting of Al/SiCp composite also follows a cyclic-dynamic process, similar to that of monolithic metal.

Ding et al. [6] concluded that the use of coolant in the cutting of Al/SiCp composite could reduce thermal softening and result in a significant reduction in the amount of workpiece material adhering to the tool surface. However, in the cutting of Al/SiCp composite with high-volume fraction particles, the cooling effect of MQL and LN2 could not prevent the workpiece material from the accumulation of worn pits, resulting in the formation of a BUE, as shown in Fig. 10 a and Fig. 11. The flushing effect of MQL and LN2 could wash away a proportion of the debonded particles from the cutting zone and reduce the three-body abrasion, and the SiC particles firmly constrained in the workpiece could also abrade the PCD inserts and form the worn pits and grooves. As a result, these worn pits and grooves promoted the adhesion of workpiece material on the rake face, and finally gave rise to the formation of the BUE. The tool grains were dragged by the adhesive material that resulted in the formation of the worn pits when the BUE debonded from the rake face. With respect to the application of Oil and

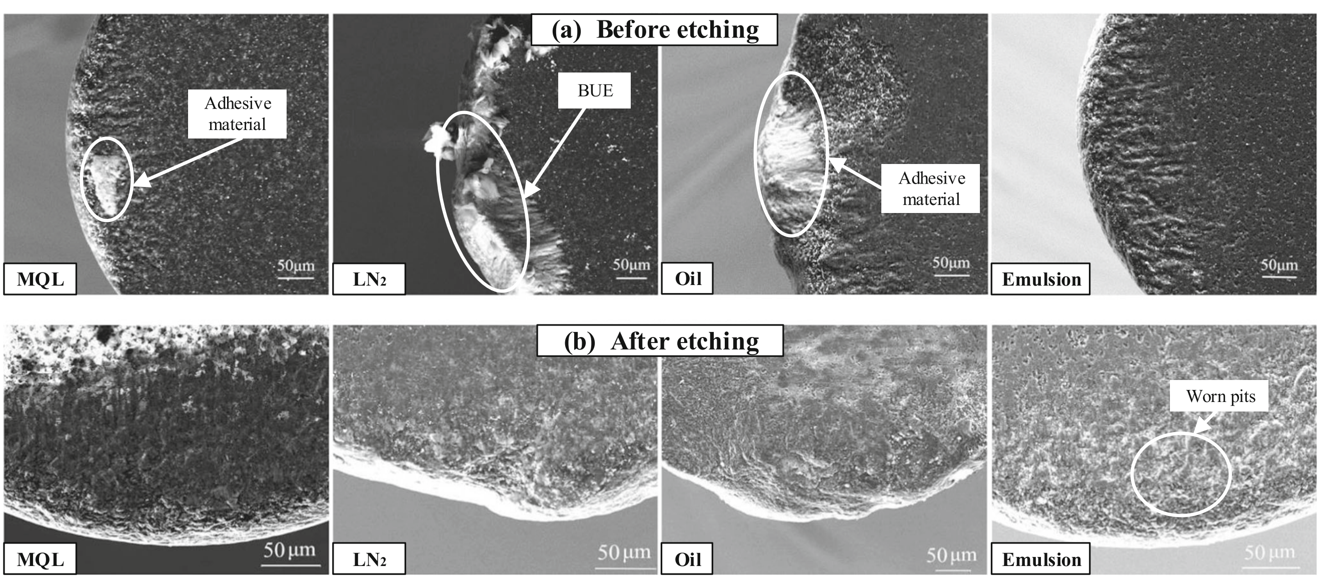

Fig. 10 Wear morphology of the rake face in turning of Al/SiCp composite under MQL, LN2, Oil, and emulsion conditions. **a** The tools used before etching and **b** the tools used after etching

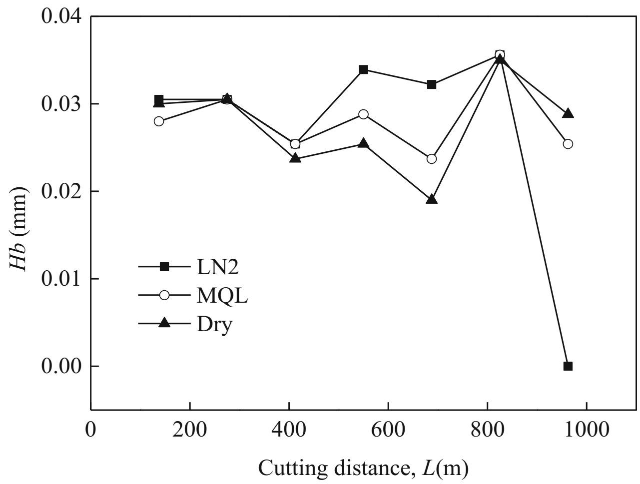

Fig. 11 Variation of BUE height with cutting distance in cutting of Al/SiCp composite under dry, MQL, and LN2 conditions

emulsion, the formation of the abrasive slurry led to hard SiC particles continuously abrading the tool surface, and the workpiece material was difficult to adhere to the rake face for a long time. The hard particles in the abrasive slurry caused the worn pits and grooves on the tool face, which still facilitated the workpiece material adhering to the tool surface. However, the adhesive material on the tool surface could also be removed by these hard particles, making it difficult to form the BUE. Therefore, adhesion pits appear on tool surface, but the process does not form the BUE in the cutting of Al/SiCp composite under Oil and emulsion environments. Under MQL and LN2 conditions, it is difficult to form the abrasive slurry in the cutting zones, and meanwhile, the worn pits and grooves caused by SiC particles abrading facilitated the adhesion of workpiece material to the rake faces.

3.4 Tool breakage

Tool breakage represents the tool failure. The rapid flank wear and severe adhesive wear can accelerate the tool breakage, and results in the failure of the cutting tool to produce an acceptable workpiece [33]. Therefore, to delay the tool breakage and increase tool life, it is worthwhile to study the tool breakage mechanism and the effects of cooling and lubrication conditions on the tool breakage in cutting of Al/SiCp composite.

3.4.1 Formation mechanism of tool breakage

During the cutting of Al/SiCp composite under dry, LN2, and Oil conditions, breakage zones were formed at the cutting edge of PCD inserts before the total cutting distance reached 1375 m, as shown in Fig. 12. From Fig. 12, no obvious damage occurred around the cutting edges before tool breakage, and the breakage zones suddenly generated on the flanks near the tool noses in the latest observations. The tool breakage was formed abruptly at a certain cutting time during the cutting of Al/SiCp composite. The microcracks were found on the rake faces away from the tool noses, as shown in Fig. 4 a, and this confirms that the tool breakage abruptly occurred without gradual and progressive wear. The formation of microcracks at the interface between the binder and tool grains could be attributed to the high-frequency hitting of the SiC particles on the tool surface, and the severe cutting vibration. During the cutting of Al/SiCp composite with 50% SiC particle, a high-volume fraction of particles in the workpiece caused more violent scraping and hitting of the reinforced particles on the tool surfaces, and thus promoted the microcrack initiation. An investigation on the chip formation mechanism in machining of Al/SiCp composite [34] suggested that the inhomogeneous distribution of the SiC particles in the machined surface resulted in the formation of segmented chips, which led to the violent cutting vibration. This vibration resulted in the cutting tool bearing an alternating load that further led to the mechanical fatigue cracks produced on the tool surfaces. The cracks caused by the particle impact and the mechanical fatigue gave rise to instability propagation on the tool faces, resulting in the tool breakage [35]. Therefore, the variation of load on the tool faces and the hitting effect of SiC particles on the tool noses are the main factors that aggravate the tool breakage during the cutting of Al/SiCp composite.

3.4.2 Effects of cooling and lubrication conditions on tool breakage

Although LN2 cutting had an excellent flushing performance that reduced the three-body abrasive wear in the cutting of Al/SiCp composite, it presented a faster tool breakage than the dry cutting, as shown in Fig. 3 c and Fig. 12 b. The reason for the rapid tool breakage under the LN2 condition can be explained in terms of the cooling effect of LN2 on the tool faces. The cooling temperature reached − 165 °C during the Al/SiCp composite turning under the LN2, which was responsible for a violent temperature variation on the cutting tools. The tool faces suffered the enhancement of thermal impact because of the violent variation of temperature. Meanwhile, the low temperature also reduced the thermal softening tendency of the workpiece material, and strengthened the support of the aluminum matrix for SiC particles. Then, this matrix strengthening effect increased the scratch and impact strength of the SiC particles and resulted in the complete shedding of the BUE from the rake faces, as shown in Fig. 12 a-LN2. The shedding of the BUE reduced the protection of tool nose, and caused the severe cutting vibration, and strengthened the mechanical impact. Therefore, the application of LN2 was found to promote the tool breakage near the tool noses. For the Oil cutting, the severe boundary wear that arose at the initial stage of the cutting process further reduced the strength of the main cutting edge that bore the alternating load and thermal impact, and resulted in rapid tool breakage. As compared with Dry, LN2,

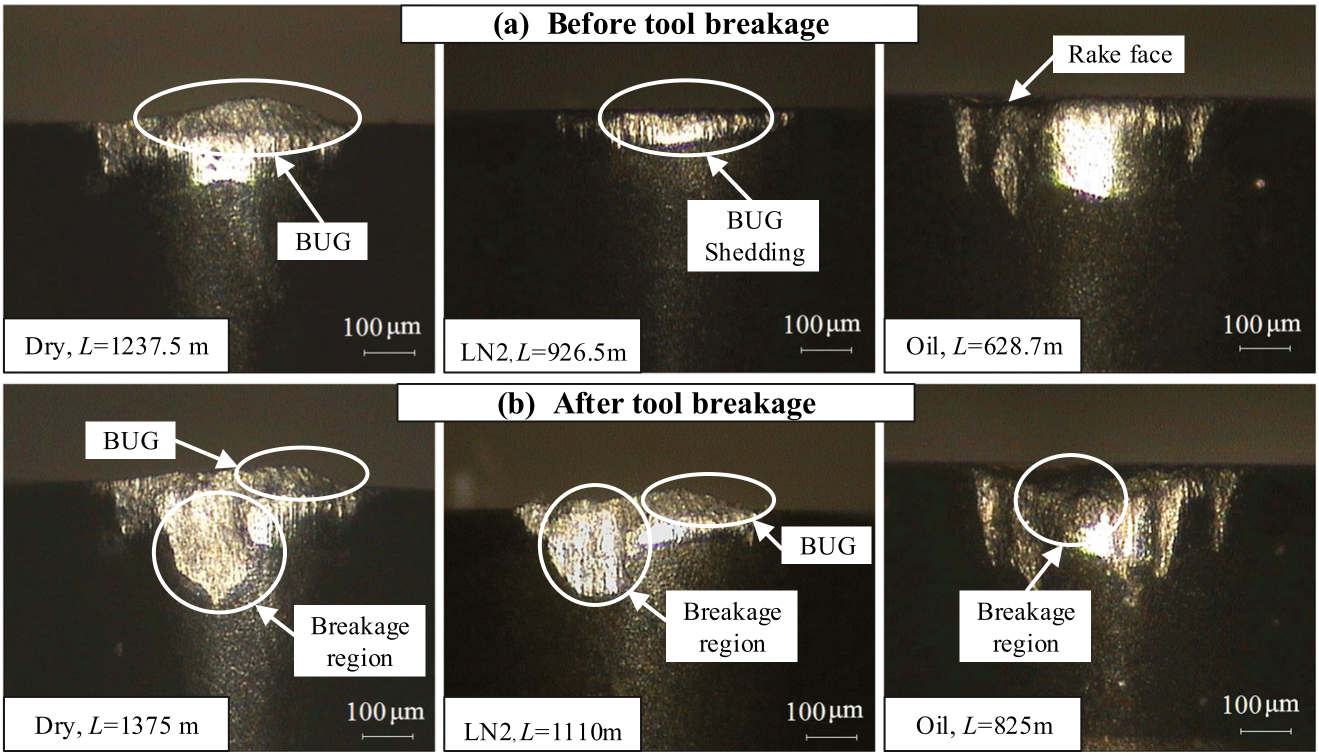

Fig. 12 Microphotograph of tool breakage of PCD inserts used in turning of Al/SiCp composite under Dry, LN2, and Oil cutting conditions. **a** The tools before breakage and **b** the tools after breakage

and Oil conditions, the MQL and emulsion cutting, with the moderate cooling effect and smooth boundary wear, are beneficial for reducing the cutting vibration and thermal impact on the tool noses. Therefore, during the cutting of Al/SiCp composite under MQL and emulsion conditions, the tool breakage caused by the thermal impact and cutting vibration was not formed before the total cutting distance reached 1375 m. According to the above analysis, the LN2 with the enhancement of the cooling effect and the Oil with severe three-body abrasion aggravated the tool breakage, while the MQL and emulsion with moderate cooling effect and smooth boundary wear could reduce the probability of tool breakage.

4 Conclusions

This study gives details of tool wear during turning of Al/SiCp composite under different cooling and lubrication conditions. The investigation results of this study can provide a guideline for selecting cooling and lubrication methods to extend tool life during machining of Al/SiCp composite. Based on the above analysis, the following conclusions are drawn.

The flank wear (including the boundary wears of major and minor flanks), adhesive wear, and tool breakage were obviously controlled by different wear mechanisms during turning of Al/SiCp composite. The boundary wear mechanism of the minor flank was abrasive wear, including two-body and three-body abrasive wears, in turning of Al/SiCp composite. Meanwhile, the major flank wear was predominantly caused by two-body abrasion. The fast tool breakage in the turning of Al/SiCp composite was found to be caused by the load variation and thermal impact on the tool faces, and the hitting effect of SiC particles on the tool noses. The formation of the worn pits and BUE on the rake faces confirmed the presence of adhesive wear in the turning of Al/SiCp composite when PCD tools were used.

On the other hand, it was found that the variation in cooling and lubricant environments has a significant impact on the flank wear, adhesive wear, and tool breakage. The MQL and LN2, with excellent flushing performance as well as excellent lubricating and cooling properties, helped to reduce the three-body abrasion at the boundary zones of the minor flanks and the major flank wear. The application of Oil and emulsion with a poor lubrication effect led to hard SiC particles continuously abrading the tool surfaces, which could avoid the adhesion of the workpiece material on rake face. However, the cooling effects of MQL and LN2 could not prevent the workpiece material from accumulating in the worn pits, resulting in adhesive wear of the PCD tool. The MQL and emulsion cutting, with moderate cooling effect and smooth boundary wear, limited the formation of tool breakage. Nevertheless, the LN2 and Oil could accelerate rapid tool breakage.

In general, MQL, with an excellent flushing property, significantly improves the performance of cooling and lubrication and reduces the abrasive wear. In addition, MQL also gives some advantages in reducing the boundary wear, tool breakage, and major flank wear. Therefore, MQL is suitable as a preferred cooling and lubrication mode in turning of Al/SiCp composites.

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