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ORIGINAL ARTICLE

Tool wear mechanisms for milling in situ TiB_2 particle-reinforced Al matrix composites

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Abstract In situ TiB_2 particle-reinforced Al matrix composite is a new kind of metal matrix composite (MMC). With in situ synthesis method, a better adhesion at interfaces is achieved and hence improves mechanical properties. Due to the presence of hard ceramic particles, the tool wear is seriously compared with traditional metal while cutting in situ TiB_2/Al MMC. Many studies have been carried out on tool wear and wear mechanisms for cutting ex situ SiC/Al MMCs. However, few papers about the tool wear for cutting in situ particle-reinforced Al matrix composites have been published. In this paper, tool wear, tool life, and wear mechanisms for milling in situ TiB_2/Al by using uncoated carbide tools were investigated. The results show that the tools were worn out at the initial tool wear stage, which indicated that the wear of tool was rapid. Among all the cutting parameters, milling speed has dominated influence on tool life, followed by feed rate and cutting depth. During milling in situ TiB_2/Al MMC, the uncoated tools suffered from abrasive and adhesive wear, chipping and peeling wear, microcracks, and diffusion and oxidation wear.

Keywords In situ · TiB_2 particle · Al matrix composite · Tool life · Tool wear · Wear mechanisms

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1 Introduction

Due to the superior properties such as improved strength, low density, low cost, and increased wear resistance, the particle-reinforced metal matrix composite (PRMMCs) has been the focus of study in the realm of metal matrix composite and it is expected to be applied on the next generation of advanced aerospace engines [1]. In general, particle-reinforced metal matrix composite can be classified into two categories according to forming methods of reinforcing particles (ex situ and in situ PRMMCs). However, the ex situ PRMMCs have been thoroughly researched on preparation, material mechanics performance, and machining performance because of the much easier preparation process, even though the material performance of in situ PRMMCs is superior.

At present, some studies have been carried out on the effect of particles on tool wear mechanisms for cutting ex situ SiC/Al MMCs. Li and Seah [2] found that the wear acceleration was caused by the interference between SiC particles. Average flank wear rate increased with the weight percentage or size of SiC particles increasing. They also noted that the main tool wear mechanisms included two-body abrasion and three-body abrasion. Same work was also done by Ozben et al. [3]. From their experimental results, it was also found that tool flank wear increased with increasing of reinforcement ratio. Besides, the abrasive reinforcement element caused more wear on tools during machining process.

The effect of coating on tool wear mechanisms has also been widely researched for cutting ex situ SiC/Al MMCs. Ciftci et al. [4] found that a coated carbide tool was more resistant to wear than uncoated tool. And abrasive wear was observed to be the main tool wear

Fig. 1 Milling tool used in experiments

mechanism. El-Gallab and Sklad [5] found that polycrystalline diamond (PCD) provided satisfactory tool life compared to other coated carbide tools. Ge et al. [6] studied the tool wear mechanism of single-crystal diamond (SCD) and PCD tools in ultra-precision turning SiC/2009Al MMCs. It was found that the major wear patterns of SCD included microwear, chipping, cleavage, abrasive wear, and chemical wear, which were mainly caused by the combined effects of abrasive wear of hard particles and catalysis of copper in the matrix material. However, as for PCD, it mainly suffered from abrasive wear on the rake face and adhesive wear on the flank face. Besides, Andrewes et al. [7] found that the initial wear of both PCD and CVD inserts was caused by abrasion due to the hard reinforcement. The further flank wear was generated by a combination of abrasion and adhesion.

The influence of cutting parameters on tool wear mechanisms for cutting ex situ SiC/Al MMCs has been experimentally studied. Manna and Bhattacharayya [8] found that the flank wear was high at low cutting speed due to the high cutting force by using uncoated carbide tools. However, at high cutting speed, the cutting edge temperature was very high and this led to rapid deformation of tool edge, which in turn caused rapid flank wear. Hence, cutting speed zone between 60 and 150 m/min was recommended. Bhushan et al. [9] carried out turning tests on 7075 Al alloy and SiC/7075 Al MMCs using carbide and PCD tools. It was concluded that turning, for carbide tool, should be carried out at a cutting speed of less than 200 m/min, feed rate of 0.1 mm/rev, and cutting depth of 0.5 mm. To PCD, it was recommended that turning should be carried out at a cutting speed higher than 220 m/min but a feed rate of less than 0.2 mm/rev and cutting depth of less than 1.0 mm. In addition, El-Gallab and Sklad [5] concluded that, for lower flank wear of PCD, the proper nose radius would be 1.6 mm and rank angle would be 0°. Cutting speed of 894 m/min, feed rate of 0.45 mm/rev, and cutting depth of 1.5 mm would lead to the smallest tool wear under dry condition.

Table 1 Specifications of the milling tool used in experiments

Specifications	Diameter	Rank angle	Nose radius	Flank angle	Helix angle	Tooth
Value	12 mm	15°	0.2 mm	12°	40°	4

Table 2 Nominal chemical composition of the 7050 Al alloy matrix

Elements	Zn	Zr	Mg	Cu	Al
Composition (wt%)	6.3	0.11	2.3	2.2	Balanced

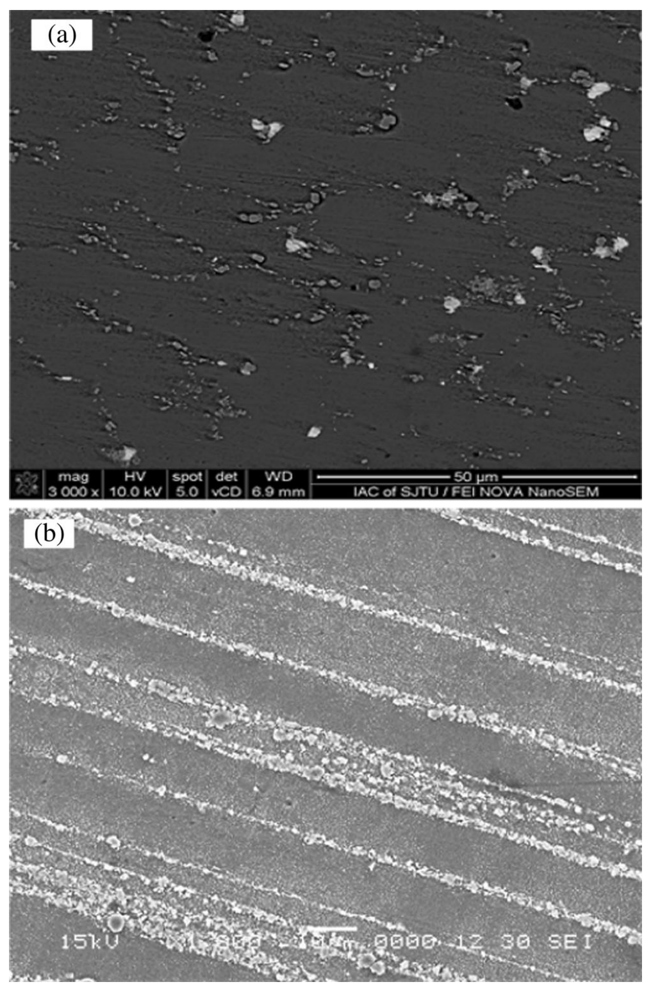

Fig. 2 Microstructure of in situ TiB_2/Al MMCs. **a** Along the transverse direction. **b** Along the longitudinal direction

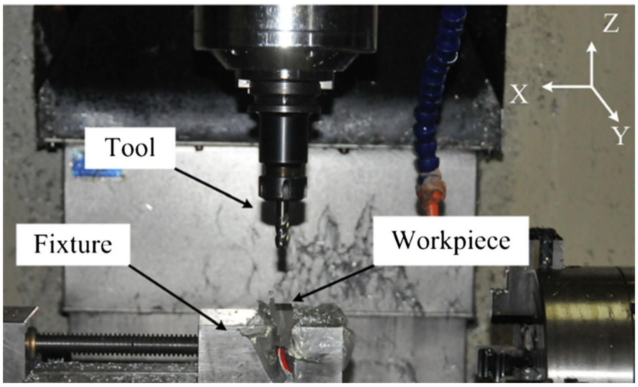

Fig. 3 Milling tests

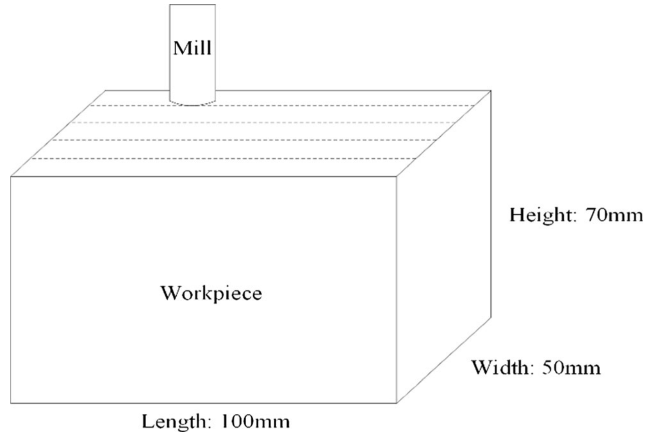

Fig. 4 Milling process in tool wear progression experiments

For in situ TiB_2/Al metal matrix composites, it has been researched for several years. The work of in situ TiB_2/Al metal matrix composites published by researchers such as Suresh et al. [10] and Ramesh et al. [11] mainly focuses on the material preparation methods, formation of particles, and wear behavior and properties such as microstructure, microhardness, ultimate tensile strength, modulus of elasticity, percentage elongation, and so on. However, for tool wear of machining in situ TiB_2/Al composites, few research has been reported, even though Anandakrishnan and Mahamani [12] have investigated the flank wear in the machining of in situ Al-6061-TiB_2 metal matrix composites.

In this paper, the influence of cutting parameters on tool life and tool wear mechanisms of uncoated carbide tools in milling in situ TiB_2/7050 Al alloy matrix composite were studied and discussed. The object of this research is to have a better understanding of tool wear patterns, wear mechanisms, and influence of cutting parameters on tool wear in cutting in situ TiB_2/Al composites.

2 Experimental procedure

2.1 Tool and material characterization

The uncoated solid carbide end milling tool used in experiments is shown in Fig. 1. Table 1 shows the specifications of the end milling tool used in this paper. The composite used was in situ 6 wt% TiB_2 particle-reinforced 7050 Al alloy matrix composite prepared and supplied by the state key laboratory of metal matrix composites, Shanghai Jiao Tong University. It was performed with an exothermic reaction process via K_2TiF_6 and KBF_4 mixed salts [13]. The particle size varies from 50 to 200 nm, and the nominal chemical composition (wt%) of the 7050 Al alloy matrix is shown in Table 2. The microstructure of the composite along the transverse direction and the longitudinal direction is presented in Fig. 2.

Table 3 Experimental parameters and their levels

No.	Factor	Notation	Level			
			1	2	3	4
1	Milling speed/(m/min)	V_c	22.62	37.70	52.78	67.86
2	Feed rate/(mm/z)	f_z	0.05	0.1	0.15	0.2
3	Cutting depth/mm	a_p	0.2	0.4	0.6	0.8

2.2 Experiment design and measurement

Machining tests were performed on a VMC-850 three-coordinate vertical CNC milling machine under dry condition as shown in Fig. 3. In this paper, factors taken into consideration for tool life and tool wear were milling speed, feed rate, and cutting depth. Levels of factors are presented in Table 3.

Flank wear (VB) was used as a criterion of tool wear [14]. All types of tool wear were observed upon reaching the criteria value of $VB_{max} = 0.3$ mm. Flank wear was measured on an Alicona IFM-G4 automatic tool scanner after a certain milling length, 500 mm, as shown in Fig. 4. Measurement of each flute was repeated twice and the average values of four flutes were reported. At the same time, the milling time of each mill was taken as the tool life. After tests, the worn out tools were etched for 30 s using a solution of 1.0 ml HCl, 1.5 ml HF, and 97.5 ml H_2O. Then, the morphologies of tools were investigated with a VEGA3LMU SEM-EDS (scanning electron microscope equipped with energy-dispersive X-ray spectrometer).

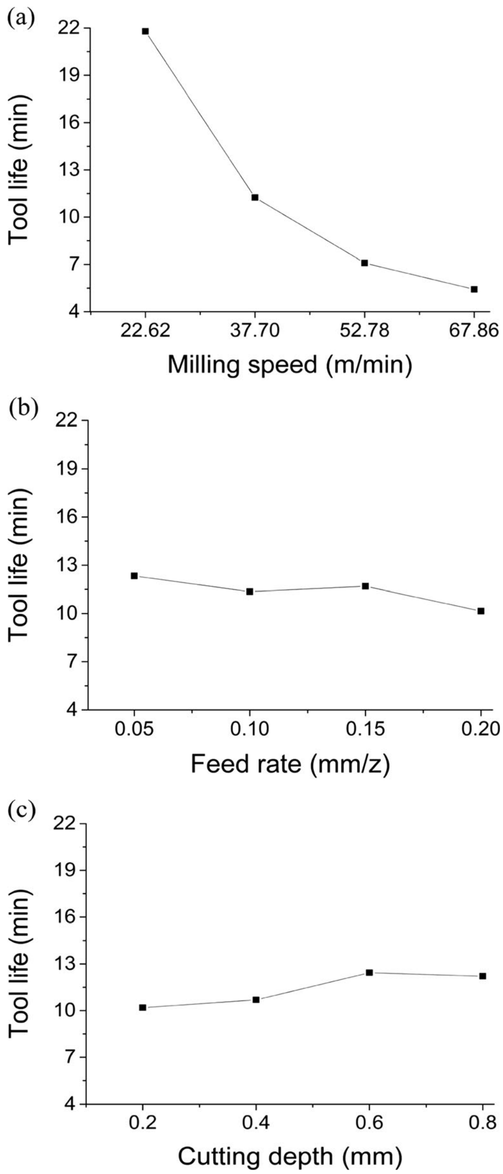

Fig. 5 Effects of milling parameters on tool life. **a** $f_z = 0.05$ mm/z, $a_p = 0.4$ mm. **b** $V_C = 52.78$ m/min, $a_p = 0.4$ mm. **c** $V_C = 52.78$ m/min, $f_z = 0.05$ mm/z

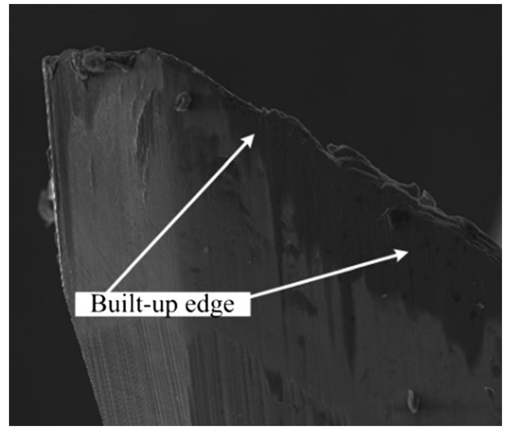

Fig. 6 BUE (built-up edge)

3 Results and discussions

3.1 Tool life and tool wear progression

In the present study, tool life is represented by the milling time before the VB value reaches to 0.3 mm. Figure 5 shows the tool life at various milling speeds, feed rate, and cutting depth, respectively.

It can be seen that milling speed has dominated influence on tool life, followed by feed rate and cutting depth. From Fig. 5a, there is a significant reduction in tool life with milling speed increasing. According to Trent and Wright [15], due to the rapid flow of the chips and workpiece past the tool cutting edges, the friction at the cutting interfaces decreases as cutting speed increases when cutting Ti-6Al-4V in high speed. However, compared to Ti-6Al-4V, the workpiece material used in this paper is much more adhesive. Hence, friction at the cutting interfaces and milling force were both kept large. Besides, the formation of unstable

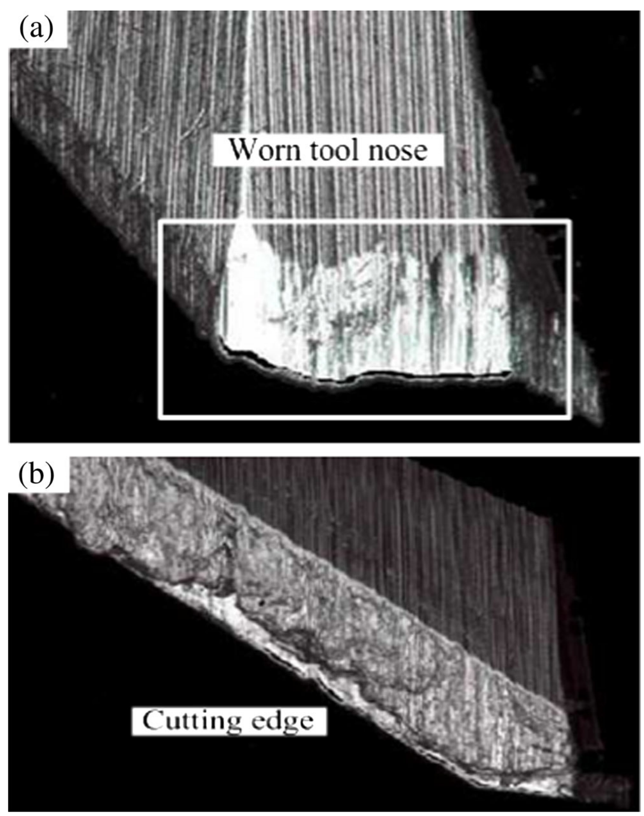

Fig. 7 Worn tool edge: **a** $a_p = 0.2$ mm; **b** $a_p = 0.8$ mm

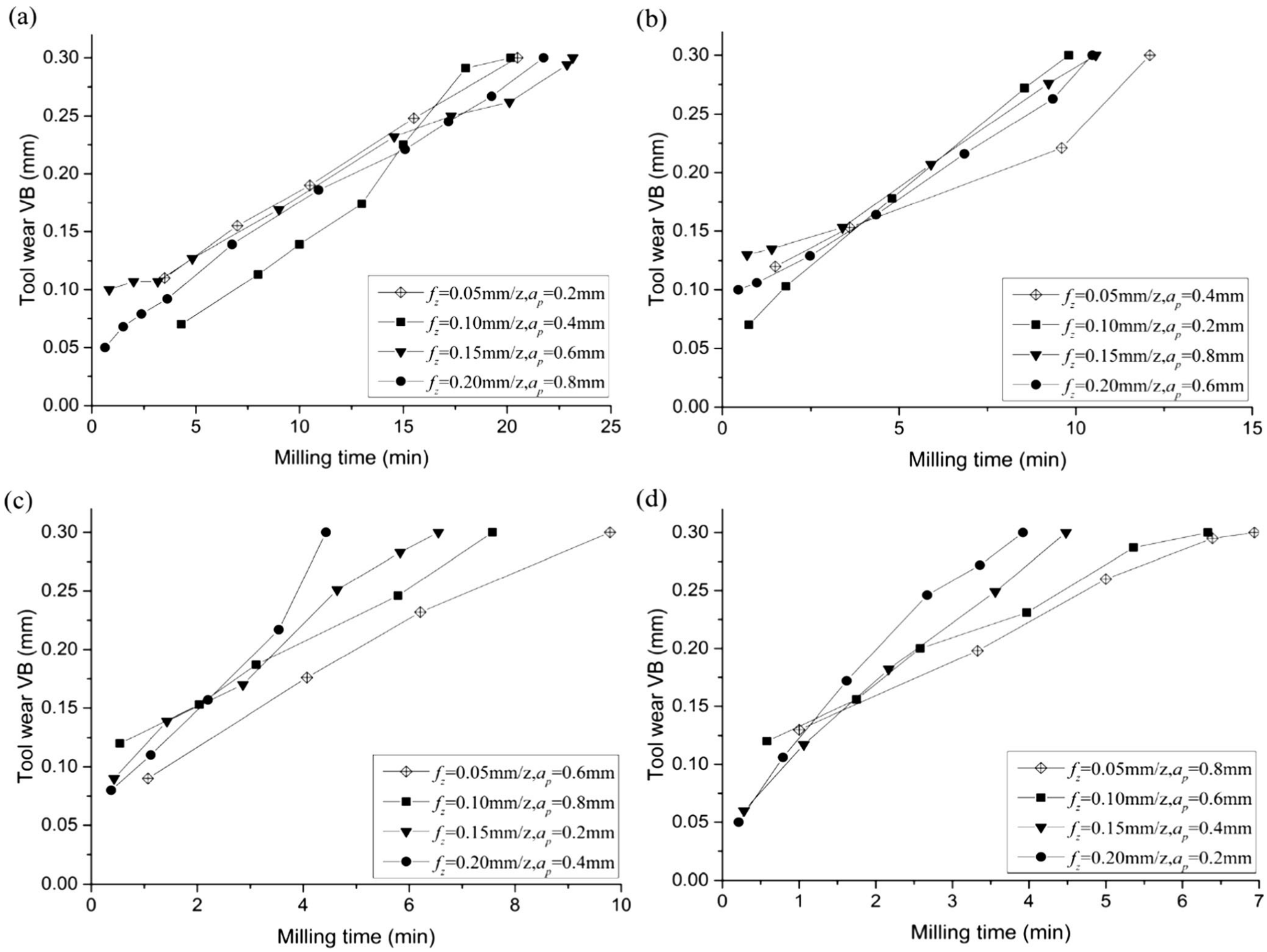

Fig. 8 Tool wear progression under different combinations of milling parameters. **a** Tool wear progression under combination of f_z and a_p ($V_c = 22.62$ m/min). **b** Tool wear progression under combination of f_z and a_p ($V_c = 37.70$ m/min). **c** Tool wear progression under combination of f_z and a_p ($V_c = 52.78$ m/min). **d** Tool wear progression under combination of f_z and a_p ($V_c = 67.86$ m/min)

larger built-up edge (BUE) at lower milling speed can protect the cutting wedge from further wear, as shown in Fig. 6. Furthermore, this is accompanied by

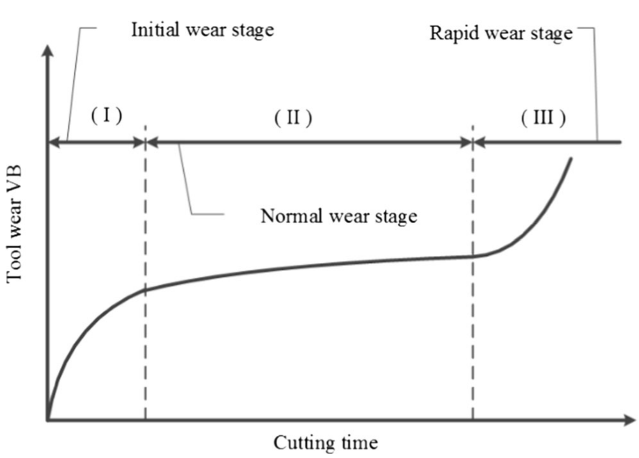

Fig. 9 Tool wear progression and tool wear stages

increasing in milling heat generation at the chip-tool and tool-workpiece interfaces, which also accelerate tool wear by thermally related wear mechanisms. As a result, tool life decreases with milling speed increasing.

In Fig. 5b and c, the effects of feed rate and cutting depth on tool life tend to be opposite. Tool life decreases slightly with increasing feed rate. This is probably because milling force increases as feed rate increases. Hence, the flank wear gets worse under a combination of large cutting force and hard ceramic-reinforced particles. Besides, due to the increasing feed rate and large friction at the cutting interfaces, milling temperature rises accordingly. As a result, tool life decreases when feed rate increases. However, tool life increases slightly when cutting depth increases from 0.2 to 0.6 mm. The tool nose is the major part of the cutter when cutting depth is as small as 0.2 or 0.4 mm. Due to the hard reinforcement and high viscosity of material,

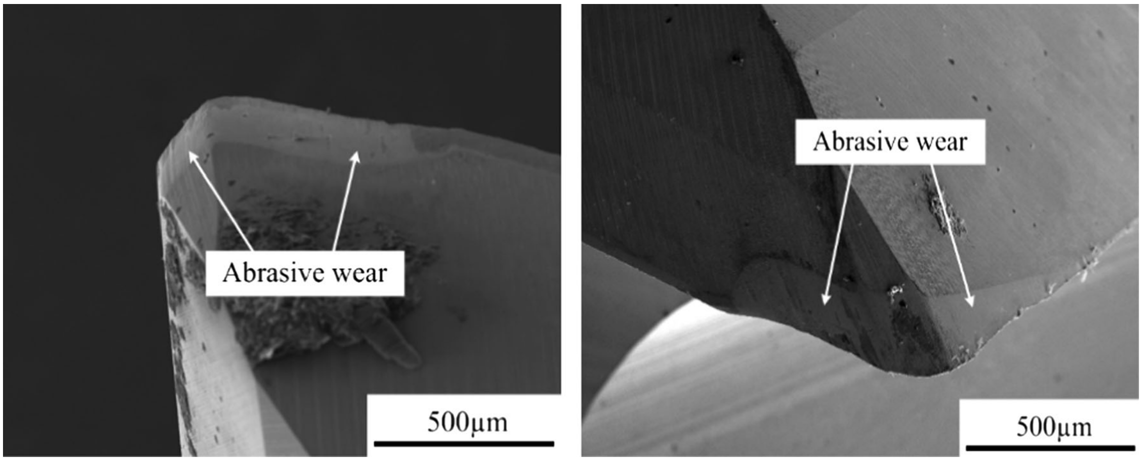

Fig. 10 Abrasive wear of tools

the cutting force is large and the nose is more likely to be worn out rapidly at the beginning of milling process, which can be seen from Fig. 7a. As the cutting depth increases, the length of cutting wedge involved in milling process increases. Though milling force gets much larger, the length of cutting wedge gets longer and unit milling force decreases, which decreases the milling force at the tool nose in return. Flank wear rate is generally lower than the tool nose wear. As a result, tool life increases slightly with cutting depth increasing.

The tool wear progressions under different milling parameter combinations are shown in Fig. 8. It can be seen from Fig. 8 that the characteristics of tool wear development are similar at different milling speeds. From pictures in Fig. 8, it is obvious that tool life decreases as milling speed increases under any combination of feed rate and cutting depth. And it seems that the combination of feed rate and cutting depth has little effect on tool wear progression. According to Chen [16], the tool wear progression can be divided into three stages as shown in Fig. 9. In the initial stage and rapid stage, the tool wear increases rapidly and tools usually become worn out in the rapid wear stage. The tool wear rate is much smaller in the normal wear stage. However, among all the tool wear progressions in the milling experiments using uncoated carbide tools, no normal wear stage has been observed obviously. Besides, the relationship between tool wear and milling time tends to be linear, which indicates that tool wear of milling in situ TiB_2/Al MMCs is quick and serious, and uncoated carbide tools are not suitable for cutting this kind of MMCs.

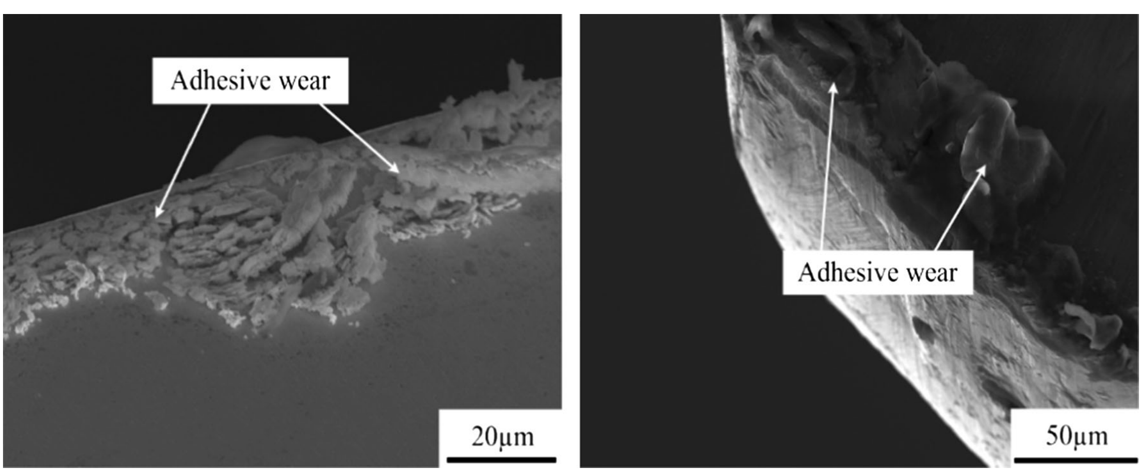

Fig. 11 Adhesive wear of tools after milling

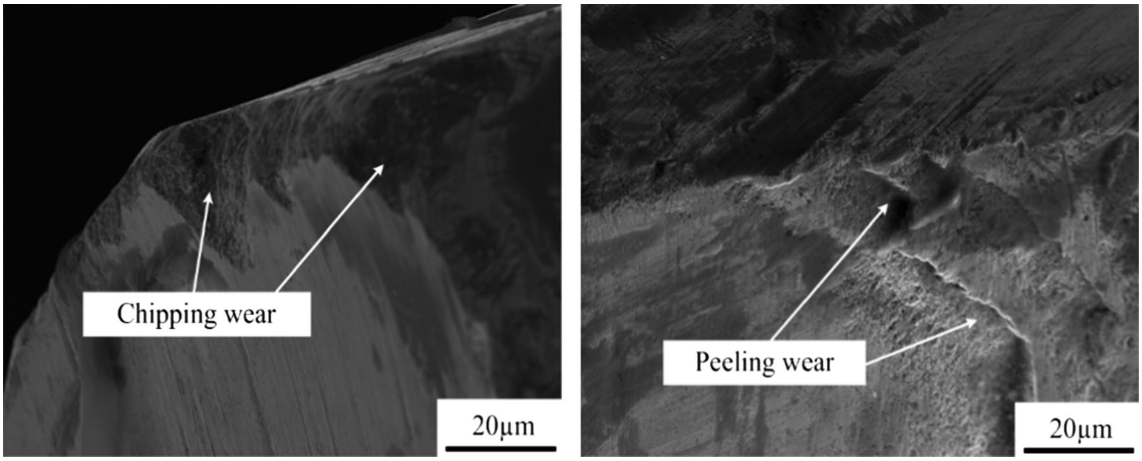

Fig. 12 Chipping and peeling wear of tools

3.2 Wear mechanisms

3.2.1 Abrasive and adhesive wear

Figure 10 shows the magnified images of the typical worn tools obtained by SEM. It can be seen from the pictures that both the flank and rake face suffered abrasive wear in milling in situ TiB_2/Al MMCs. The wear degree on rank face is much slighter than flank face. Also, there is no obvious sign of fine grooves and particle scratch found on the wear land of flank face. This is quite different from the observation of cutting ex situ SiC/Al MMCs [7, 17–19]. Since the MMC embedded extremely hard and abrasive ceramic reinforcements, the cutting edge and flank surface of tools will be destroyed by these ceramic particles. Besides, the particle size is small, which makes particles more difficult to be fractured or pulled out from matrix material individually. This is also the reason why there are much small grooves found in the machined surface rather than fractured and pulled out particles, which are quite different from that of cutting ex situ SiC/Al MMCs.

Additionally, due to the high contact pressure and milling temperature between workpiece and tool, adhesive wear is frequently found on the cutting edge as shown in Fig. 11. Adhesive wear mechanism occurs when there is chemical affinity between the tool and workpiece material. Due to the coarse characteristic of the cutting edge coupled with the high adhesive nature of the aluminum matrix, chip material is much easier to be adhered to the tool cutting edge in a short time. The adhering layer somewhat protected the tool flank face against further abrasion.

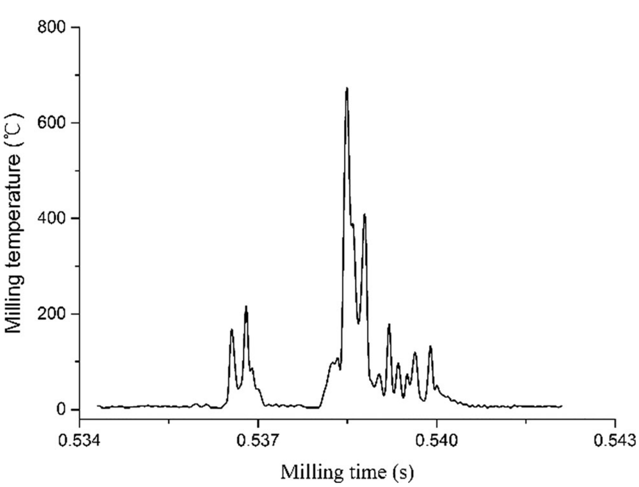

Fig. 13 Milling temperature during milling process

3.2.2 Chipping, peeling wear, and microcracks

Even though the hardness and strength of composites are improved and symmetrical with the presence of TiB_2 particles, there are still some relatively soft parts in the material due to the small size (50 to 200 nm) and low volume (6 wt%) of ceramic particles in matrix material. During milling in situ TiB_2/Al MMCs, the tool cut the soft and hard material alternately. Hence, the tool suffered from alternate stresses during the whole milling process. In this situation, microchipping and microfracture were formed on the cutting edge [6]. Once microchipping and microfracture occur, stress concentration may exist in these areas. As a result, the tool will suffer from bigger chipping and peeling wear, which are shown in Fig. 12.

For cutting tool, together with severe alternate stresses, it also suffers from high milling temperature,

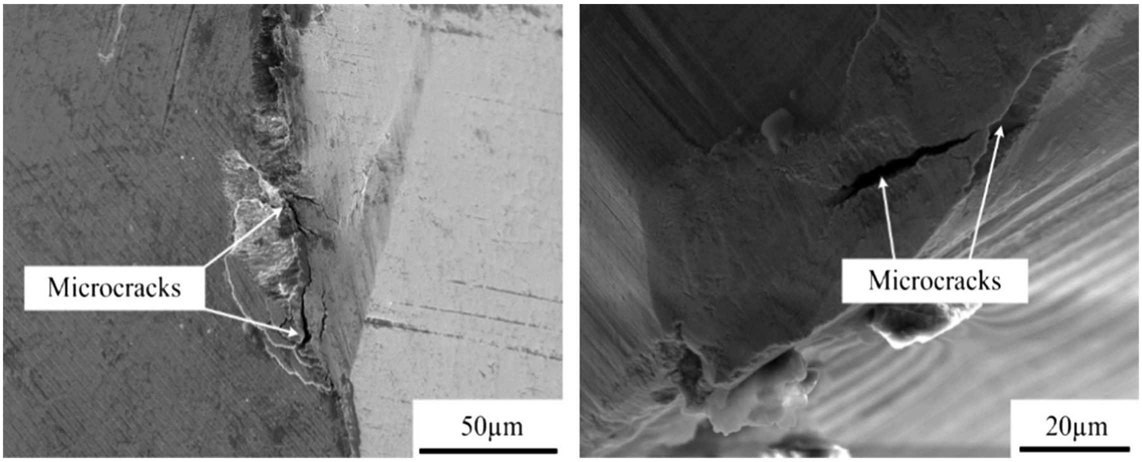

Fig. 14 Microcracks on tool edge

which was measured with an embedded semi-artificial thermocouple, as shown in Fig. 13. The milling temperature is highly localized at the tool edge (in the sticking region), specifically at the tool nose. In Fig. 14, microcracks were found on the cutting edge. It can be attributed to the severer mechanical (alternate stress) and thermal (high milling temperature) impact during milling in situ TiB_2/Al MMCs. Due to the higher milling temperature and severer thermal impact, the odds of the microcracks, chipping, and peeling wear are raised.

3.2.3 Diffusion and oxidation wear

Figure 15 and Table 4 show the results of EDS analysis of worn tools after corrosion. From Table 4, it can be seen that a large amount of elements such as Al, Ti, Cu, and Mg was found on the worn tool edge, which is the obvious evidence of diffusion wear. During milling process, due to the alternate stress and improved hardness of composite, the tool edge is easy to be worn out in a short time. Then, the matrix material is becoming soft and adhered on the worn tool edge under the effect of high milling temperature and large milling force. With discontinuous thermal and mechanical impact, some elements from the matrix material and chips such as Al, Cu, and Ti are diffused into the worn tool edge faces, which change the composition and structure of milling tools. Hence, it makes the milling tools easier to be fatigued and accelerates the tool wear. Usually, the diffusion wear occurs with abrasive wear under high milling temperature and milling force.

Besides, a large amount of oxygen element from the air was also found. This is because aluminum, which comes from

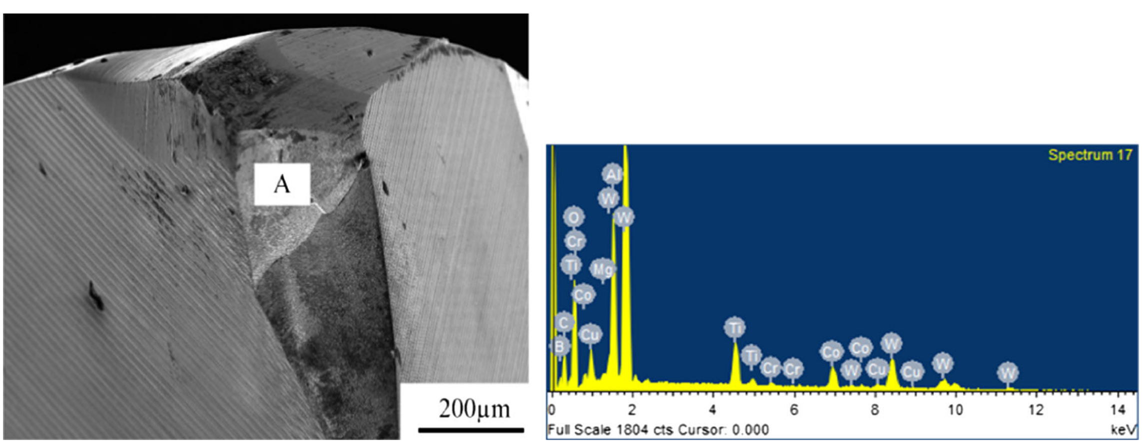

Fig. 15 Diffusion wear on tool edge

Table 4 EDS of point A

Element	Weight%	Atomic%
O	20.86	27.29
Mg	0.25	0.21
Al	5.22	4.05
Ti	4.17	1.82
Cr	0.43	0.17
Co	4.17	1.48
Cu	1.22	0.40
W	63.68	64.58
Total	100.00	

the chips, is much easier to react with oxygen under high milling temperature. Also, tungsten and cobalt in the tool react with oxygen during the milling process, since the transient temperature is as high as 700 °C, which is shown in Fig. 13.

3.3 Chip forming

Figure 16 shows the typical chips formed during milling process. Unlike ex situ SiC/Al MMCs, there are no segmented chips [20]. C-type and helix chips are very commonly found during milling in situ TiB_2/Al MMCs. This is because the interface between particles and matrix material is cleaner and has a better adhesion.

Chips were examined by using SEM. The chip surface morphologies are shown in Fig. 17. According to Ernst [21], chip shapes are classified into three categories: continuous chips, continuous chips with BUE, and discontinuous chips (saw-tooth and serrated type). It is obvious that chips obtained during milling in situ TiB_2/Al MMCs are discontinuous. In Fig. 17a, it can be seen that the joint inner surface is smooth and it reflects the surface quality of machined surface. Besides, the obvious cutting mark of the tool nose can also be found on the joint inner surface. Figure 17b presents the saw tooth at the free surface of chips. Saw-tooth chips are usually formed in hard milling at high speed. And in

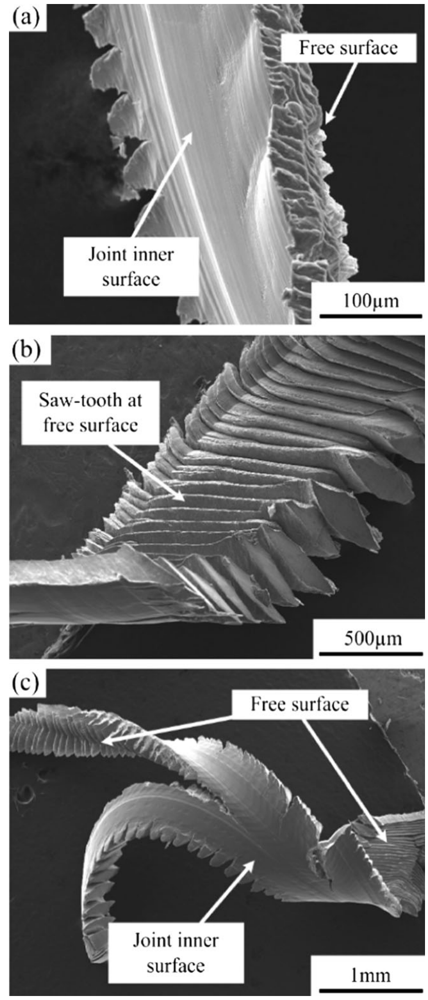

Fig. 17 Chip morphologies. **a** Joint inner surface and free surface. **b** Saw tooth. **c** Chip tearing

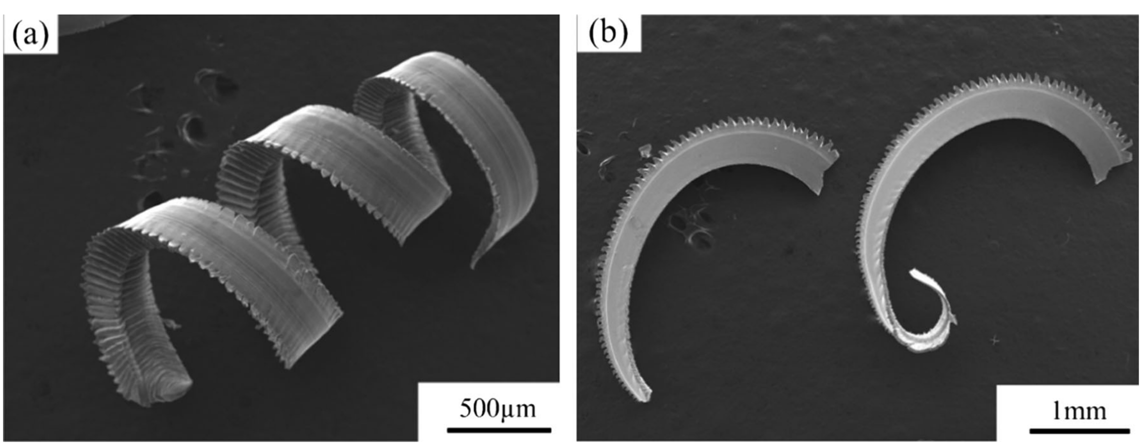

Fig. 16 Typical chip formations. **a** Helix chip. **b** C-type chip

Fig. 17c, it is observed that there is tearing in chips. It is probably because of the uneven distributed heat and strain stress during the milling process.

4 Conclusions and scope of future work

In this paper, the wear mechanisms of a brand new material, in situ TiB_2/Al MMCs, on uncoated carbide tool were investigated. The tool life was measured at various cutting speeds, feed rate, and cutting depth. Meanwhile, the corresponding wear formation, tool wear progression, and chip formation were examined. Based on the experiment results, the wear mechanisms were analyzed and discussed. Some conclusions can be drawn as the following.

1. Tool wear is serious in milling in situ TiB_2/Al MMCs with uncoated carbide tools. Tool life is various from 3 to 20 min. Among all the milling parameters, milling speed has the dominated influence on tool life, followed by feed rate and cutting depth. There is a significant reduction in tool life as the milling speed increase due to the combination effect of high milling temperature and large milling force. On the contrary, feed rate and cutting depth have little influence on the tool life.
2. The relationship between tool wear and milling time tends to be linear under different milling parameter combinations, which indicates that uncoated carbide tools were worn out at the initial tool wear stage. And uncoated carbide tools are not suitable for milling in situ TiB_2/Al MMCs.
3. The main tool wear mechanisms are abrasion, adhesion, chipping, and peeling wear. Microcracks and diffusion and oxidation wear occur due to high milling temperature and large milling force.
4. Chips formed during the milling process tend to be helix and C-type. The chip shape was discontinuous and saw teeth were observed at the free surface of chips. Also, some tears were found on chips. This may be caused by the uneven distributed thermal stress and force stress.

Generally, tool wear was studied experimentally in this paper. In fact, theoretical analysis is needed if we want to get a deeper understanding of wear mechanism. Aiming at this, we will try to establish a mathematic model for cutting force of in situ Al-MMC in the near future.

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