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ORIGINAL ARTICLE

Tool wear morphologies and mechanisms for cutting C_f/Mg composites

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Abstract Existence of carbon fibers in C_f/Mg composites resulted cutting tools to be worn rapidly by the contact and relative sliding between tools and workpiece during cutting operations. In order to investigate tool wear in the cutting operations of C_f/Mg composites, carbide tool and polycrystalline diamond (PCD) tool were used to machine the C_f/Mg composites by dry cutting, and tool wear morphologies were observed and analyzed. The experimental results showed that there was a lot of workpiece material stagnation zone in front of the cutting edge due to fracture-based chip formation of the C_f/Mg composites. The wear morphologies of carbide tool was corner wear in the cutting edge maximum slant, in which wear mechanisms were mainly abrasive wear, adhesion wear, and microbreakage. The wear of carbide tool was fast, and its tool life was 40~50 min. The wear morphologies of PCD tool were microbreakage in the edge of the blade, adhesion wear, and abrasive wear, and the wear of PCD tool was in a lower level and its tool life was longer than that of carbide tool.

Keywords Carbon fiber · Composites · Tool wear · Carbide · Polycrystalline diamond · Cutting

1 Introduction

Carbon fiber-reinforced magnesium matrix composites (C_f/Mg) were fabricated by the combination of carbon fibers and magnesium alloy. Therefore, C_f/Mg composites showed low density, high specific strength and stiffness, good wear resistance, high temperature resistance, impact resistance, and good dimensional stability for the addition of continuous carbon fibers [1–3]. Due to their superior performance, C_f/Mg composites presented a broad potential application in the aerospace, automotive, and other high-technology fields. It was possible to manufacture high-quality C_f/Mg components through liquid fabrication technique, but additional cutting was inevitably to achieve surface finish and dimensional tolerance in the assembly operations between the C_f/Mg composite components and other connection components. The cutting of C_f/Mg composites was very complex due to the hard abrasive nature of carbon fiber in the composites, which would result in the tool wear rapidly during the cutting operations. When the tool wear reached a certain extent, the deteriorated surface integrity and dimension error would be caused with increasing cutting force and vibration. Then, the tools have to be replaced to guarantee the desired cutting quality. It mainly manifests that the high-speed steel tool suffers extreme wear and presents a very short tool life, so the cutting force is increased rapidly and makes a serious loss in accuracy and surface quality [4–6]. Experience acquired from the cutting of conventional metal materials cannot be transplanted to those of C_f/Mg composites. The cutting of C_f/Mg composites have become one of the problems in their application.

Friction in the cutting of composites was a result of complicated physical, chemical, and thermomechanical phenomena [7]. The investigations on the tool wear and machinability of composites were mainly focused on carbon fiber-reinforced resin composites and particle reinforced metal matrix composites [8–11]. The features of tool wear for cutting composites with carbide tool, ceramic tool, and cubic boron nitride (CBN) tool have been researched. They found that the tool wear was extensively caused by the very hard and abrasive reinforcements, and directly affected the cutting precision and surface

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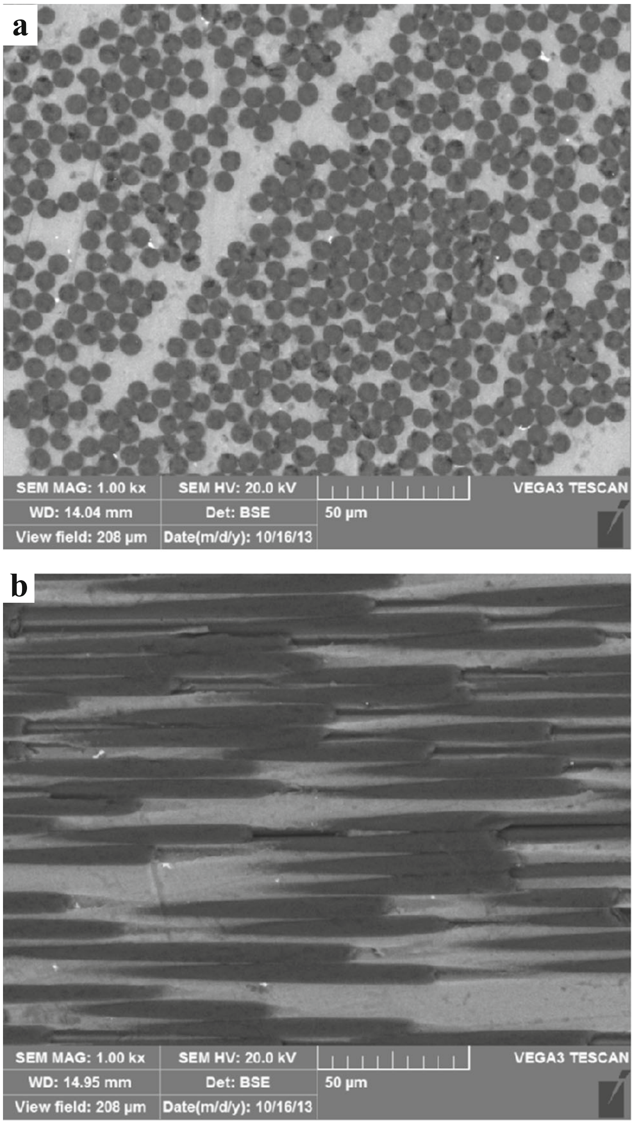

Fig. 1 Microstructure of C_f/Mg composites: **a** cross section, **b** vertical section

quality. Rahman et al. [10] carried out the cutting of carbon fiber-reinforced composites with the tools of uncoated tungsten carbides, ceramic, and cubic boron nitride (CBN), and found that CBN tool showed superior tool wear properties as compared against other tool materials, and ceramic tool was unsuitable for machining composites because ceramics is prone to mechanical and thermal shock. Basavarajappa [11] studied the tool wear in cutting Al 2219/15SiCp-3Gr composites with carbide, coated carbide, and polycrystalline diamond (PCD) tools and reported that the PCD tool showed better wear resistance properties than carbide and coated carbide tools. Muthukrishnan et al. [12] investigated the tool wear in the cutting of SiC particle-reinforced aluminum matrix composites and found that the major damage mechanism was abrasive wear for conventional tools and brittle break for high hardness tools. Dai et al. [13] studied the effects of fiber volume fractions and cutting parameters on tool wear, which showed that PCD and CBN tools were suitable for the cutting of Al_2O_3+C_f/ZL109 composites, and the tool wear increased with the increasing of fiber volume fraction. From the literatures, it was found that the machining of MMC is an important area of research in the application of MMC, so the selection of tool material and cutting rule of C_f/Mg composites was the urgent problem in their application.

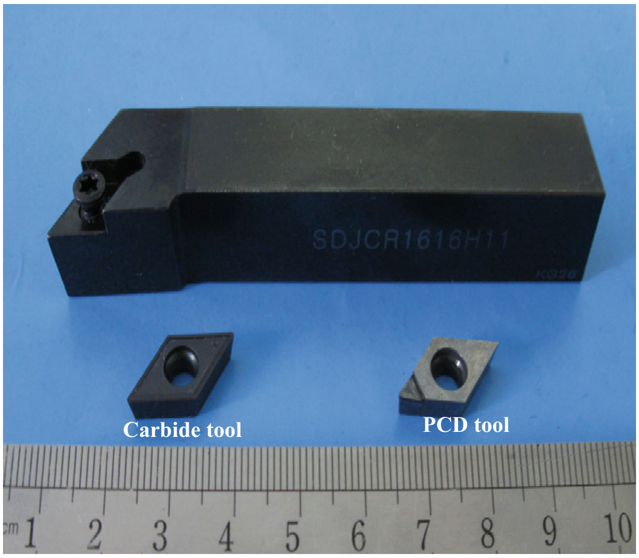

Fig. 2 Tools

In this study, carbide tool and PCD tool were selected for the investigation of tool wear in the cutting of C_f/Mg composites. The tool wear morphologies were observed by scanning electron microscopy, and the tool wear mechanisms were revealed. This study provided an experimental basis for the cutting and application of C_f/Mg composites.

2 Experimental

2.1 Fabrication of C_f/Mg composites

The C_f/Mg composites were fabricated by direct extrusion following vacuum pressure infiltration technique [14]. Pyrolytic carbon was deposited on the surfaces of carbon fibers to reduce the interface reaction by chemical vapor deposition. The chemical compositions of AZ91D magnesium alloy are 8.30–9.70 % Al, 0.35–1.00 % Zn, 0.15–0.50 % Mn, ≤0.10 % Si, ≤0.03 % Cu, and balance Mg. The preform was

Table 1 Elements of carbide tool

Elements	WC	TiC	Cr_3C_2	Co
Weight percentage	84	10.5	3	2.5

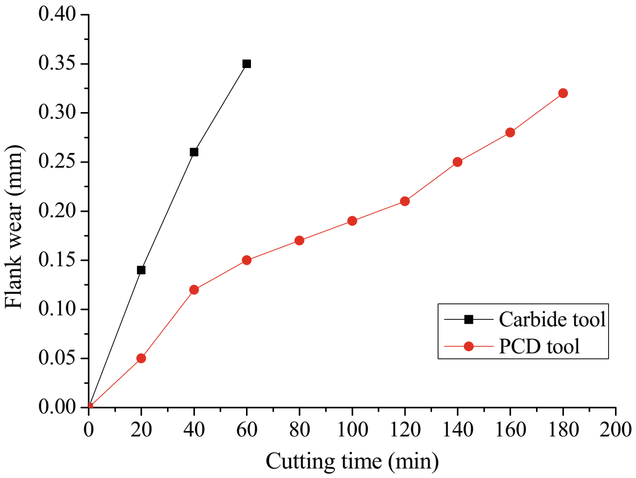

Fig. 3 Relation curves of VBmax with cutting time

preheated, and the AZ91D was melted in their furnaces, respectively. Then, the mold cavity was pumped to the vacuum state at 0.02 MPa after temperature-keeping of 10~15 min, and the molten magnesium alloy was poured into the mold by the pressure of compressed argon [15, 16]. The molten magnesium was infiltrated into the carbon fiber preform under the pressure from the movement of punch. The dimension of C_f/Mg composite workpiece was a diameter of 140 mm× 160 mm. The microstructure of C_f/Mg composites indicated that the dense composites and uniform distribution of carbon fibers could be achieved, as shown in Fig. 1. The volume fraction of carbon fiber was 40 %.

2.2 Cutting process

In this research, the experiments were limited to the cutting of a cylindrical component. The test machine was CS6140 general lathe. The cylindrical lathe turning was conducted in the condition of dry cutting. Three-jaw chuck was used to install and fix the cylindrical workpiece. The cutting process parameters were given as follows: linear cutting speed 46 m/min, cutting depth 0.15 mm, and feed rate 0.15 mm/r. Tool wear quantity was tested every 20 min. MU7025 carbide tool and PC750 PCD tool were used, as shown in Fig. 2. The elements of carbide tool are shown in Table 1.

2.3 Test

The tool wear area was considered as the criterion that would affect the results of cutting process. The measurement of tool flank wear width was used to evaluate the tool wear [9]. MM-400/LM measuring microscope was used to test the flank wear of main cutting edge, and the maximum wear amount of flank wear (VBmax=0.3 mm) was selected as the wear indicator. TESCAN VEGA II scanning electron microscope (SEM) was used to observe the tool wear morphologies for analyzing the wear mechanism. Wear surface morphologies, profile phase, and element chemistry configuration of tool wear were analyzed using scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS).

3 Results and discussions

3.1 Tool life

The tool life can be defined as the period of time that tool cutting edges lose their usefulness through the wear amount [17]. A relationship between flank wear VBmax and cutting time were measured by monitoring the tool wear amount of carbide tool and PCD tool in the cutting of C_f/Mg composite materials, as shown in Fig. 3.

The tool wear amount of carbide tool and PCD tool were increased with the increase of cutting time. Carbide tool wear increased more quickly and showed a large amount of tool wear. The curve of carbide tool reached a constant slope. The tool wear standard was reached in 40~50 min. The wear amount of PCD tool was small, and tool wear process is slow. The life cycle of PCD tool can extend up to 180 min, and the

Fig. 4 Tool wear of carbide tool and its EDS

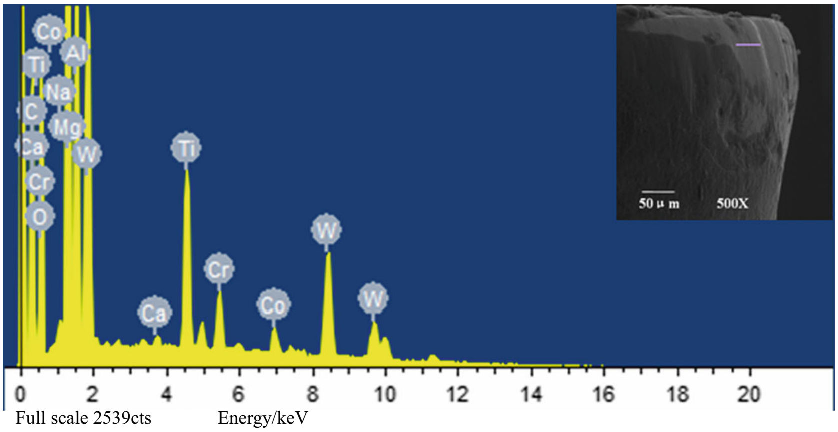

Table 2 Element analysis of the used carbide tool

Elements	Carbide tool	
	Weight percentage	Atomic percentage
C K	22.89	42.87
O K	21.96	30.87
Mg K	10.59	9.80
Al K	9.06	7.55
Ti K	9.60	4.51
Cr K	2.21	0.95
Co K	2.07	0.79
W M	21.63	2.65
Total	100.00	–

amount change of tool wear was relatively stable. In normal wear stage, the tool wear of carbide cutting was about two times compared with that of PCD tool. PCD was a synthesizing sintered diamond micropowder compacts with cobalt metal binder under the condition of the high temperature and high pressure, and showed crystals randomly oriented, isotropy, homogeneous hardness. Therefore, PCD tool could bear a large number of processing heat duo to its high hot hardness and thermal stability, and brittleness damage along the cleavage plane was not easy to occur, which produced a long life cycle with fine sharpness. That was the main reason for the difference performance between the two tools. PCD cutting tool should be selected to satisfy the cutting precision and stability of C_f/Mg composites.

3.2 Tool wear morphologies and their EDS

The purpose of analyzing these tool wear micrographs was to identify the wear mechanisms. The chip formation was a complicated process with magnesium alloy sheared breaking and carbon fibers fracture, and the tools were worn by continuous abrasion of carbon fibers. Severe friction existed in the contact area between the tool flank surface and the cutting surface for the carbon fiber fracture and matrix shear in the cutting process, which leaded to the high contact pressure and temperature, so the tool wear would develop in the tool flank surface and the tool edge [18]. Because the cutting process is complex, different tool wear patterns appear at the same time [19].

Being a mainstay of the cutting industry for a long time, carbide tool was a powder metallurgy product by the sintering of high hardness and micron grade refractory metal carbide powder (WC, TiC, Cr_3C_2, etc.) and binder (Co). Grinding crack was produced for the continuous friction surface between the carbon fibers and carbide tool in the constant brush at the beginning. The carbide tool was often subjected to the cyclic mechanical impact loads at the same time, which contributed the flaking on partial region of the tool surface. Since the viscosity of the magnesium alloy in the C_f/Mg composites, the elements of C_f/Mg composites were adhered to the surface of the carbide tool, such as Mg, Al, Zn, and other elements of carbide tool. The rake face wear features of the carbide tool are shown in Fig. 4.

The element analysis of the used carbide tool by EDS is shown in Table 2.

PCD tool was not easy to react with the C_f/Mg composites workpiece and present many features, such as super high hardness, high thermal stability, low friction, and high wear resistance, which makes it possible to be widely used in the machining field [10]. Serious coherence and obvious groove were observed from the PCD tool surface. The flank wear was caused by the continuous friction in the contact area between the tool surface and the cutting surface. The rake face wear features of the PCD tool and its EDS are shown in Fig. 5. The element analysis of the used PCD tool by EDS is shown in Table 3.

Fig. 5 Tool wear of PCD tool and its EDS

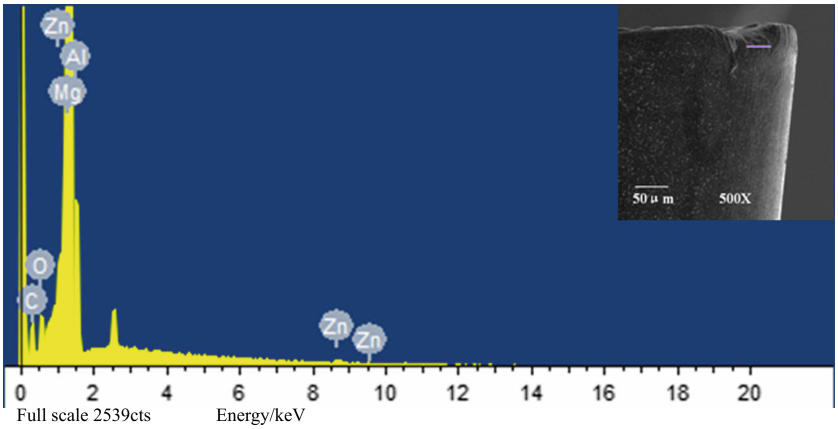

Table 3 Element analysis of the PCD tool

Elements	PCD tool	
	Weight percentage	Atomic percentage
C K	9.49	17.45
O K	1.98	2.73
Mg K	84.14	76.46
Al K	3.92	3.21
Zn K	0.48	0.16
Total	100.00	–

Through the EDS of the PCD tool tip, the elements of magnesium alloy can be found obviously.

3.3 Tool wear mechanism

Tool wears can be observed in the carbide tool and PCD tool, which microstructures are shown in Figs. 6 and 7.

The main tool wear mechanisms are listed as follows:

1. Abrasive wear

The mechanical action between the workpiece chip and tool was the mechanism that generated abrasive wear, which was appeared on the tool surface. Abrasive wear caused by the removal of the tool and was triggered by the attrition mechanism [20].

Obvious abrasive wear was caused by the sliding friction in the presence of hard carbon fibers embedded the magnesium alloy matrix and existed on the carbide tool and PCD tool, respectively, also can be considered as microcutting. The high-strength carbon fibers showed lots of hard points for their high hardness in the cutting of C_f/Mg composites, so the tool material was removed away by the mechanical action of hard fibers in the contact interface passing over the tool face and the grooves were sliced on the tools [21]. Moreover, a tensile deformation had occurred in the carbon fibers before cutting, and an elastic recovery was generated after cutting, which produced an amount of pressure on the tool surface [22]. The cutting between tool and workpiece material can be seen as the grinding, so the surface scratches was presented as zigzag performance and existed along the cutting speed direction.

The aforementioned wear phenomenon was abrasive wear and existed in the whole process of tool failure. The hardness of diamond was higher than that of carbide, so the wear extent of carbide tool was significantly higher than that of PCD tool, and good abrasive wear resistance was presented in PCD tool.

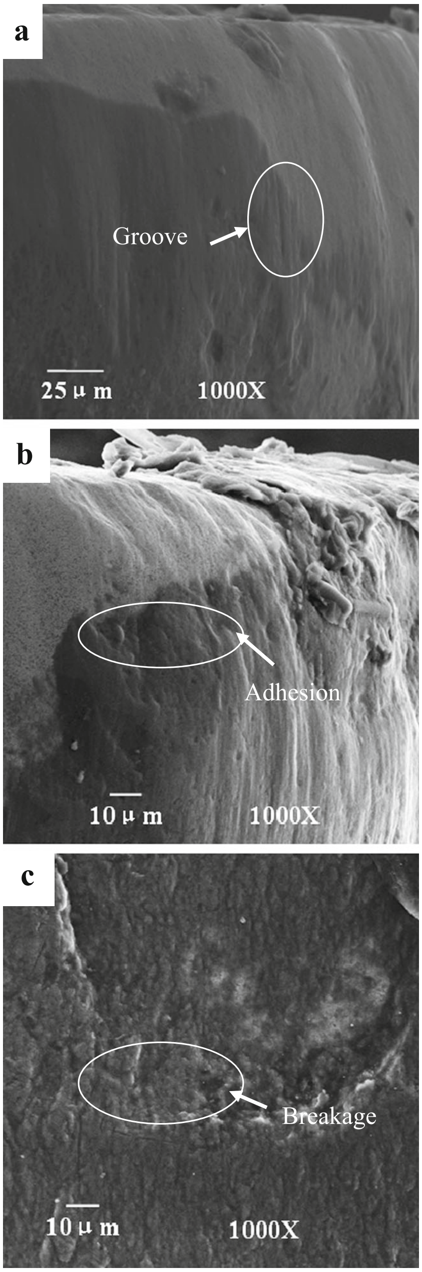

Fig. 6 Tool wear morphologies of carbide tool: **a** groove, **b** adhesion, **c** breakage

2. Adhesion wear

Adhesion is the combination phenomenon in the contact between the tools and C_f/Mg composites. Adhesive wear is caused by the formation and fracture of asperity junctions between the cutting tool and the workpiece. In the cutting process, a lot of cutting heat was produced by the friction between tool and workpiece, which softened the matrix alloy, thus increased the cutting resistance. Short and chopped carbon fibers were packaged by matrix alloy, which would form a sticking point in contact area under the contact pressure and

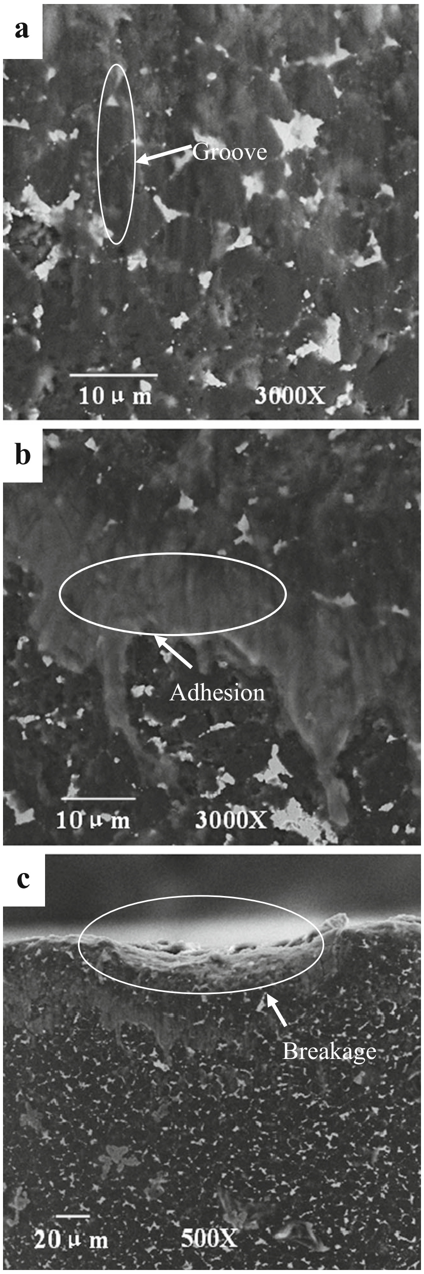

Fig. 7 Tool wear morphologies of PCD tool: **a** groove, **b** adhesion, **c** breakage

the molecular scale distance. The chip would firmly consolidate in the tool surface with the unceasing change of temperature. A consolidated cutting edge fracture presented in the contact area and part tool materials was took away, so adhesive wear occurred. The statistical EDS analyses of the adhesion on the tool rake face can be seen in Tables 2 and 3.

The tool surface of the carbide tool contained the elements of C, O, Mg, Al, W, and Ti, which included the elements of the C_f/Mg composites and the carbide tool. The tool surface of the PCD tool contained the elements of C, O, Mg, Al, and Zn, which included higher elements of AZ91D than that of carbide tool. The adhesion of AZ91D magnesium alloy was caused by shear stress or tensile stress in the relative motion between the surface of tool and C_f/Mg composites in the cutting process. A bonding layer of AZ91D materials showed the evidence of adhesion of the C_f/Mg composites on the tool surface due to the high chemical activity of the magnesium alloy and the strong affinity on the tool under the effect of high temperature and high pressure during cutting process. The bonding layer was easy to fall off from the carbide tool surface under the mechanical shock, so flaking is inevitably and the particles of tool surface also are taken away; then, the adhesion wear occurred [23]. The bonding layer continuously fell off and recreated in the cutting process, which contributed to the adhesion wear. From Tables 2 and 3, the adhesion of tool surface with large amounts of magnesium alloy could be observed, and the tool wear degree of carbide was greater than that of PCD.

3. Microbreakage

Microbreakage was the small gaps at the cutting edge of tool and appeared more significantly in the PCD tool than that of carbide (seen Fig. 7c). When the impact toughness of the tool was insufficient, it was likely to develop the microbreakage on the cutting edge. C_f/Mg composites were made of high-strength low-density fibers and magnesium alloy matrix, so the composites showed uneven hardness in the inner. In the cutting process, the carbon fibers were removed as brittle separation. Material removal was a discontinuous process duo to the scattered distribution of the carbon fibers, so the cutting tool was under intermittent load [24]. The microbreakage was due to the repeated action of loop contact stress from the periodic vibration [25]. Microbreakage appeared on the tool edge finally, and the cutting ability was reduced.

4 Conclusions

1. The tool wear was caused by the grinding and the shock from the difference performance of the magnesium alloy and the carbon fibers. Surface topographies of the tools indicated that the main wear features of carbide tool were mainly given as abrasive wear and the secondary feature was impacted, and the wear features of PCD tool were mainly given as microbreakage, and the complementary feature was abrasive wear.
2. The wear mechanisms of carbide tool were categorized into the abrasive wear, adhesion wear, and microbreakage on the tool surface. The wear mechanisms of PCD tool included microbreakage, abrasive wear, and adhesion wear. Abrasive wear mainly

occurred on the flank edge area of the carbide tool and PCD tool.

3. PCD tool presented a higher wear resistance compared with the carbide tool in the dry cutting process and was suitable for the cutting of C_f/Mg composites.

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References

1. Hufenbach W, Andrich M, Langkamp A, Czulak A (2006) Fabrication technology and material characterization of carbon fiber reinforced magnesium. J Mater Process Tech 175:218–224
2. Korner C, Schaff W, Ottmuller M, Robert F (2000) Carbon long fiber reinforced magnesium alloys. Adv Eng Mater 2(6):327–337
3. Qi L, Tian W, Zhou J (2015) Homogenization of transverse elastic properties of C_f/Mg composites at an elevated temperature and containing a small fraction of liquid phase. Compos Sci Technol 117:234–243
4. Jia P, Zhou M (2012) Tool wear and its effect on surface roughness of glass soda-lime cut by diamond tool. Chin J Mech Eng-En 25: 1224–1229
5. Gururaja S, Ramulu M, Pedersen W (2013) Machining of MMCs: a review. Mac Sci Technol 17:41–73
6. Rawat S, Attia H (2009) Wear mechanisms and tool life management of WC–Co drills during dry high speed drilling of woven carbon fiber composites. Wear 267:1022–1030
7. Li B (2012) A review of tool wear estimation using theoretical analysis and numerical simulation technologies. Int J Refract Met Hard 35:143–151
8. Wang X, Kwona PY, Sturtevant C, Kim D, Lantrip J (2013) Tool wear of coated drills in drilling CFRP. J Manuf Process 15:127–135
9. Seeman M, Ganesan G, Karthikeyan R, Velayudham A (2010) Study on tool wear and surface roughness in machining of particulate aluminum metal matrix composite-response surface methodology approach. Int J Adv Manuf Technol 48:613–624
10. Rahman M, Ramakrishna S, Prakash J, Tan D (1999) Machinability study of carbon fiber reinforced composite. J Mater Process Tech 89:292–297
11. Basavarajappa S (2009) Tool wear in turning of graphitic hybrid metal matrix composites. Mater Manuf Process 24:484–487
12. Muthukrishnan N, Murugan M, Prahlada K (2008) Machinability issues in turning of Al-SiC(10p) metal matrix composites. Int J Adv Manuf Technol 39:211–218
13. Dai H, Liu Y, Gao Y, Du J (2005) Experiment study on tool wear of Al_2O_{3f}+C_f/ZL109 hybrid composites. Tribology 25:436–440 **(in Chinese)**
14. Liu J, Qi L, Guan J, Ma Y, Zhou J (2012) Compressive behavior of Csf/AZ91D composites by liquid–solid extrusion directly following vacuum infiltration technique. Mat Sci Eng A-Struct 531:164–170
15. Qi L, Su L, Zhou J, Guan J, Hou X, Li H (2012) Infiltration characteristics of liquid AZ91D alloy into short carbon fiber perform. J Alloy Compd 527:10–15
16. Guan J, Qi L, Liu J, Zhou J, Wei X (2013) Threshold pressure and infiltration behavior of liquid metal into fibrous preform. T Nonferr Metal Soc 23:3173–3179
17. Wei W, Xu J, Fu Y, Yang S (2012) Tool wear in turning of titanium alloy after thermohydrogen treatment. Chin J Mech Eng-En 25(4): 776–780
18. Arokiadass R, Palaniradja K, Alagumoorthi N (2012) Prediction and optimization of end milling process parameters of cast aluminum based MMC. T Nonferr Metal Soc 22:1568–1574
19. Azmi A, Lin R, Bhattacharyya D (2012) Experimental study of machinability of GFRP composites by end milling. Mater Manuf Process 27:1045–1050
20. Montoya M, Calamaz M, Gehin D, Girot F (2013) Evaluation of the performance of coated and uncoated carbide tools in drilling thick CFRP/aluminium alloy stacks. Int J Adv Manuf Technol 68:2111–2120
21. Nevesa D, Diniza A, Limab M (2013) Microstructural analyses and wear behavior of the cemented carbide tools after laser surface treatment and PVD coating. Appl Surf Sci 282:680–688
22. Cui X, Zhao J, Dong Y (2013) The effects of cutting parameters on tool life and wear mechanisms of CBN tool in high-speed face milling of hardened steel. Int J Adv Manuf Technol 66:955–964
23. Azmi A, Lin R, Bhattacharyya D (2013) Machinability study of glass fiber-reinforced polymer composites during end milling. Int J Adv Manuf Technol 64:247–261
24. Palanikumar K (2008) Application of Taguchi and response surface methodologies for surface roughness in machining glass fiber reinforced plastics by PCD tooling. Int J Adv Manuf Technol 36:19–27
25. Saini S, Ahuja I, Sharma V (2012) Residual stresses, surface roughness, and tool wear in hard turning: a comprehensive review. Mater Manuf Process 27:583–598