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ORIGINAL ARTICLE

The micro-cutting performance of cermet and coated WC micro-mills in machining of TC4 alloy micro-grooves

Yishun Wang[1,2,3] · **Bin Zou**[1,2,3] · **Chuanzhen Huang**[1,2,3] · **Zhanqiang Liu**[1,2,3] · **Peng Yao**[1,2,3]

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Abstract

Compared with commercial CrTiAlN-coated WC micro-mills, self-developed Ti(C_7N_3)-based cermet micro-mills were evaluated by milling of TC4 alloy micro-grooves. Tool damage, micro-milling forces, and surface quality of micro-grooves were analyzed to examine the cutting performance. The main wear mechanisms of cermet and WC micro-mills were dominated by micro-chipping, flank wear, built-up edge, and adhesive wear. Except for these failure modes, coated WC micro-mills had broken. The peak-to-valley (P-to-V) feed and normal forces using the coated WC micro-mills were much higher than cermet micro-mills. And micro-grooves milled by cermet and coated WC micro-mills achieved a good surface roughness. The top burrs were first found at the cutting distance of 12 mm using cermet micro-mills, but the top burrs appeared during the entire machining using coated WC micro-mills. These results indicated that cermet micro-mills were more suitable for micro-milling TC4 alloy than coated WC micro-mills.

Keywords Micro-mills · Cermet · Cutting performance · Tool damage · Micro-groove quality · TC4 alloy

1 Introduction

Nowadays, micro-products and components have an ever-increasing demand for industrial applications including electronics, optics, aerospace, biotechnology etc. Micro-milling is one of the best candidates to produce the components with complex 3-D geometries over a wide range of material types [1]. In micro-milling process, the main drawback is the poor cutting performance of micro-mills owing to their low flexural stiffness and unreliable edge strength. The higher cutting performance requires a tool material to have a better fracture toughness and hardness. As is known, diamond and WC are generally used as micro-tool materials. Because diamond is the hardest material on the earth, diamond can be manufactured into micro-mills with very sharp tips. But diamond micro-mills are only used to machine the nonferrous metals and are not suitable for cutting ferrous metals due to the high chemical affinity between diamond and ferrous materials. For manufacturing of micro-components, coated WC micro-mills are applied and investigated widely [2]. Few investigations focused on cermet as micro-mills material because it was usually considered that cermet tool material was so brittle that it was only used to manufacture cutting inserts in the conventional micro-semi-finishing or finishing. Our previous studies [3, 4] proved that Ti(C_7N_3)-based cermet inserts could really finish-turn 17-4PH martensitic and austenitic stainless steels for 50~85 min at a high speed, and also analyzed the effects of the cutting parameters on tool life and surface quality to examine the performance of Ti(C_7N_3)-based cermet inserts. Our group also developed a Ti(C_7N_3)-based cermet micro-mill with a diameter of 0.99 mm, and it exhibited a better micro-cutting performance and control ability to surface qualities in machining of aluminum alloy 2024 [5]. Based on these previous works, we further designed and developed this Ti(C_7N_3) cermet micro-mill with a smaller diameter of 0.8 mm to investigate the cutting performance in comparison with coated WC micro-mills based on tool damage,

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✉ Bin Zou
zb78@sdu.edu.cn

[1] Centre for Advanced Jet Engineering Technologies (CaJET), School of Mechanical Engineering, Shandong University, 17923 Jing Shi Road, Jinan 250061, People's Republic of China

[2] Key Laboratory of High Efficiency and Clean Mechanical Manufacture, Ministry of Education, Shandong University, Jinan, People's Republic of China

[3] National Demonstration Center for Experimental Mechanical Engineering Education, Shandong University, Jinan, People's Republic of China

micro-milling force, and surface quality in micro-milling of TC4 alloy micro-grooves.

Because of small tool diameter in the range of 1–999 μm, micro-milling cutter is easily worn and even fractured when machining difficult-to-cut-material, which surely induces some great changes of micro-milling force, surface quality, and machining efficiency. TC4 alloy is considered as difficult-to-cut-material because of its unique high strength-weight ratio, exceptional corrosion resistance, and poor thermal properties [6]. To avoid the rapid tool wear and short tool life, the coated micro-mills exhibited good cutting performance in micro-milling of titanium alloys [7]. Oliaei and Karpat [8] found the wear modes of WC-Co micro-mills including flank wear and edge rounding on the cutting edges. Aramcharoen et al. [2] found that CrTiAlN coatings could help to reduce the edge chipping and edge wear as compared to uncoated WC micro-mills, and wear patterns of coated micro-mills were identified as coating delamination while flank wear was found on TiAlN-coated micro-mills. Although coatings have the high hardness and low friction coefficients, they are easily peeling off from the tool substrate. Because the variable stress, strain, and strain-rate fields affect the film-substrate deformations, and thus resulting in coating fatigue failure [9]. Moreover, coatings increase the cutting edge radius, which can lead to a raise in the cutting force [10]. These are the most key problems which should be carefully taken into consideration in application of coated WC micro-mills.

Measurement of cutting force during machining provided useful information about tool condition and represented the actual state of machining [1]. The milling forces in micro-milling are usually smaller than those experienced in conventional machining. Liu and Shashidhara [11] found that the magnitude of the P-to-V feed forces did not increase monotonously with cutting distance. Instead, the feed forces had a zigzag pattern of increase due to the mixed effects of edge chipping and abrasive wear on the micro-milling forces. However, few studies paid attention to investigations of the micro-milling forces with tool wear progression.

Surface quality has a significant impact on the component performance. There are many factors affecting the surface quality of components, including the cutting parameters, mechanical properties of material, tool wear, cutter geometry, and so on. The most important aspects of surface quality include surface roughness and burr formation. Surface roughness is a widely used index of component quality, and it has an important effect on fatigue life of micro-components. Filiz et al. [12] found that increasing the cutting length was seen to result in lower roughness values at higher feed rates. This could be experienced by considering the increased corner radius due to wear. Yuan et al. [13] investigated the effect of cutting edge sharpness on the machined surface roughness and found that the sharper cutting edge radius would improve the surface finish. Burrs, which are an undesired but unavoidable by-product of most machining processes, cause many problems in assembly and precision component operation. According to the 3-D micro-ball end milling operation FEM simulation, Chen et al. [14] found an interesting type of burr lying on the slot base, and the newfound type of burr could be divided into three categories: entrance slot base burr, exit slot base burr, and slot side base burr. The slot side base burrs were most significant among these slot base burrs. Because of the material tearing after chip separation, a small fraction of chip was left behind on the base of the slot, which happened under improper cutting velocity and when employing blunt cutting edge to process ductile materials. Uriarte et al. [15] found that the ideal case of reducing burr formation would have a cutting tool with a very small edge radius. However, it is difficult to obtain a very small edge radius for coated WC micro-mills because of the grain size of WC and coating thickness [2].

In this work, a difficult-to-cut-material of TC4 alloy was chosen as workpiece to compare the cutting performance of cermet and coated WC micro-mills. Therefore, the main objective of this work was to explore and seek evidences revealing the advantages of cermet micro-mills in micro-milling of TC4 alloy.

2 Experimental procedure

The photograph and SEM micrographs of cermet and coated WC micro-mills are given in Fig. 1. This kind of cermet micro-mills was manufactured by four steps. Firstly, the compact cermet disks were sintered using a hot-pressing technology. Secondly, these hot-pressured disks were cut into bars using the wire-cut electrical discharge machining (WEDM) and then were ground by the precision centerless grinding machine. Thirdly, the tool handle was manufactured by the cylindrical grinding machine. Finally, the cutting tip such as cutting edges and flutes were manufactured by precision tool grinding machine (ShapeSmart NP4, ROLLOMATIC, Switzerland). The cermet micro-mills was designed with two flutes, a diameter of 0.8 mm, helix angle of 30°, and mean edge radius of 1.60–2.45 μm. A commercial CrTiAlN-coated WC micro-mill (MXH230, NS Company, Japan) was chosen as the contrasting tool, because it is appropriate to machine TC4 alloy micro-components as recommended by supplier. The geometrical parameters of coated WC micro-mills are a diameter of 0.8 mm of two flutes, helix angle of 30°, and mean edge radius of 2.94–3.77 μm. Figure 2 shows the procedures of measuring the cutting edge radius. A vertical line was made at the tangent line of the cutting edge, and the curve of the tool edge could be gained, and then the cutting edge radius was processed through a procedure based on the curve-fitting application of MATLAB.

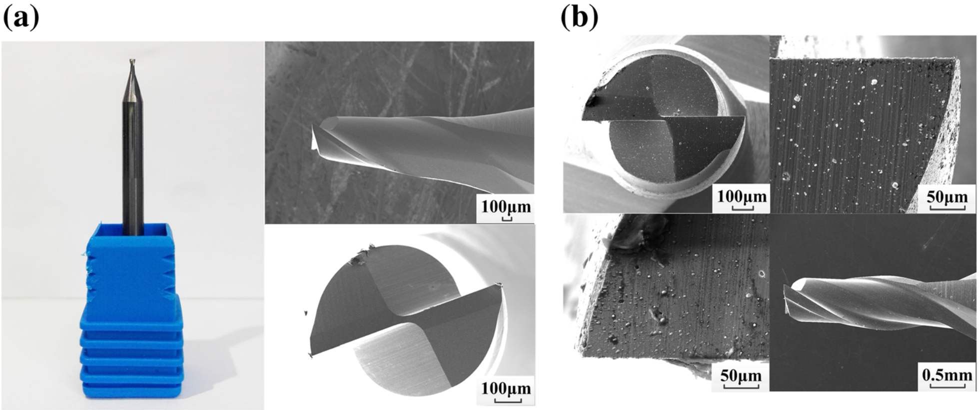


Fig. 1 The photograph and SEM micrographs of **a** cermet micro-mills and **b** coated WC micro-mills

The milling experiments were performed under a dry condition on the ultra-precision 5-axis micro-machining center (Nanotech 350FG, Moore Tool Company, England). The machining parameters were cutting speed of 60 m/min, feed velocity of 0.001 mm/tooth, and depth of cutting of 0.1 mm, which are the optimum cutting parameters for CrTiAlN-coated WC micro-mills recommended by tool supplier. To compare the cutting performance and investigate the machining mechanism, two cermet micro-mills and two coated WC micro-mills were used. It is found that both of two cermet micro-millers exhibited very good performance without facture, and only wear characteristics were found on the cermet micro-mills. One of two WC micro-mills was fractured during machining and another was worn quickly. In order to research the tool wear and tool failure, we selected the coated WC micro-mills which was fractured during machining. And we also chose the cutting force using the coated WC micro-mills that was not fractured during machining as the research object. A new tool was used for each test case, and SEM images of each tool were collected before and after the experiments, respectively. The cutting force signals were acquired by using a charge amplifier (5080A) and piezoelectric dynamometers (9119A, Kistler, Switzerland) for micro-milling and an acquisition of signals by considering a 20-KHz sampling frequency. After each test, the worn micro-mills, micro-slots (each slot was 83 mm), and burrs were observed using a laser scanning microscope (LSM, VKX200K, Keyence, Japan), scanning electron microscopy, and energy-dispersive spectroscopy (SEM and EDS, SUPRA55, Germany). Figure 3 shows the procedures of measuring the micro-groove width. A vertical line was made at the side wall of a microgroove so that the cross-section of the micro-grooves at the vertical line could be obtained, and then the micro-groove width of the bottom was measured. We used the micro-grooves of the bottom as

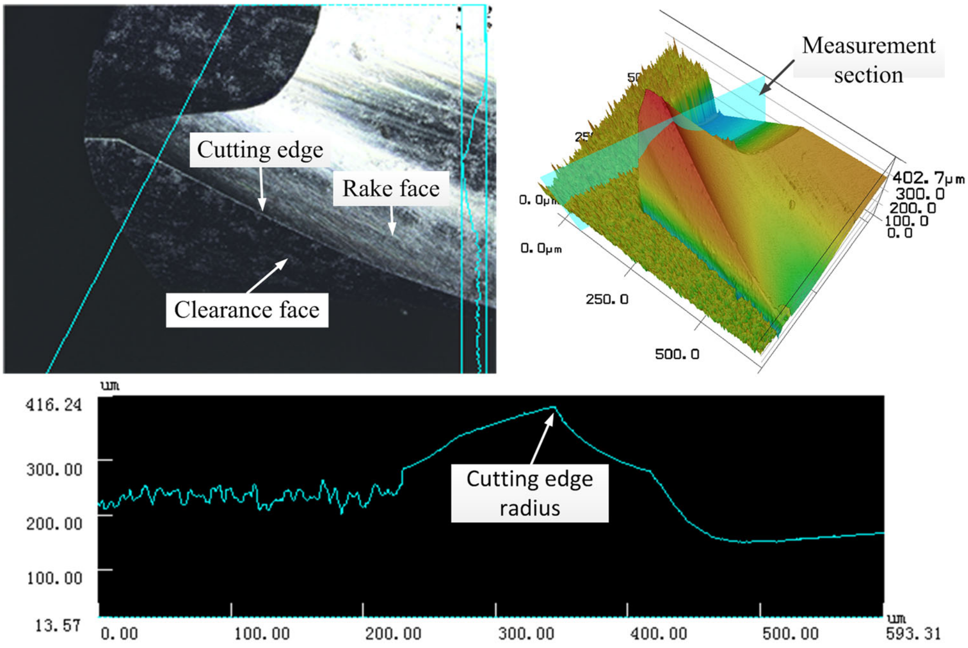


Fig. 2 The procedures of measuring the cutting edge radius

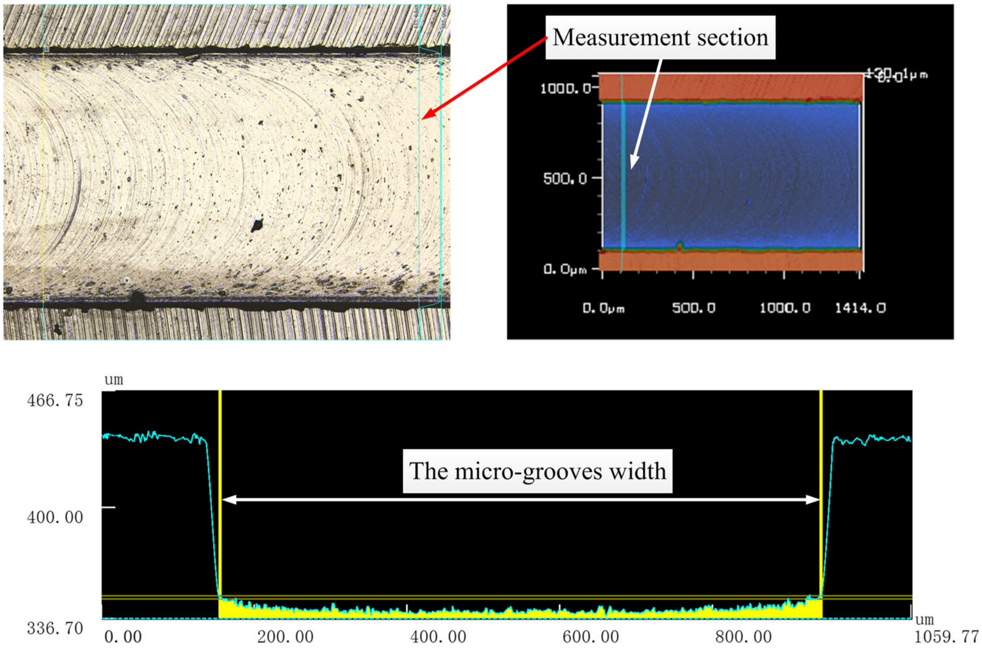


Fig. 3 The procedures of measuring the micro-groove width

the micro-groove width. A surface profiler (NT1100, Veeco, America) was used to measure surface roughness of micro-grooves.

3 Results and discussions

3.1 Tool wear

In micro-milling, there are no unified methods to appraise the tool wear which represented the change of tool size from its original size during machining. Because the width variation of the milled micro-groove could reflect the diameter situation of micro-mills, the width of micro-grooves was used as a measure of tool wear. Figure 4 shows the width variation of the milled micro-groove with the cutting distance using cermet and coated WC micro-mills, respectively. For the cermet micro-mills, the micro-groove width varied from 784 to about 768 μm, indicating that the diameter reduction of cermet micro-mills was about 2%. This also implied that the cutting edge of cermet micro-mills could keep sharp and did not become blunt during machining. The varying trends of micro-groove width revealed that the tool wear of cermet micro-mills consisted of three periods: at first, the cermet micro-mills entered a relative stable period; then, its wear developed quickly; finally, it remained a relative stable stage again; this process was not similar to the conventional process of tool wear. The cermet micro-mills could maintain good wear resistance, which was ascribed to its higher micro-hardness of 28–30 GPa [5]. After the cutting distance of 83 mm, SEM micrographs of cermet micro-mills wear were shown in Fig. 4b. The micro-chipping and chip on the flank face were found, and there was no large flank wear. The tool geometry of cermet micro-mills maintained good edge strength and sharp cutting edge. Figure 4c shows the SEM micrographs of coated WC micro-mills with the cutting distance of 166 mm. The width of flank face of coated WC micro-mills was wider than cermet micro-mills, indicating that there was more contact area between the flank face and machined surface of workpiece material, and this situation could lead to a higher cutting force on the coated WC micro-mills. Micro-cavities were also observed on the tool flank, which could seriously cause the stress concentration. The width of the milled micro-grooves exhibited an unstable change for coated WC micro-mills. After cutting of 166 mm, the width of the milled micro-grooves suddenly became wider. Since one tool tip of the coated micro-mills was suddenly broken, an imbalance in the two flutes of the coated micro-mills could lead to a higher runout. Goto et al. [16] found that the effective tool diameter of micro-mills increased with increasing the tool runout. As a result, the larger the micro-tool diameter, the more width of the milled micro-grooves will be.

To gain an understanding of the mechanism of wear, SEM images and EDS micrographs of tool wear of cermet micro-mills are shown in Fig. 5. After a machining distance of 166 mm, built-up edge (BUE) and a little micro-chipping on tool tip could be found. BUE replaced the cutting edge, so the tool material of cermet micro-mills reduced the contact with the chip and the machined surface. In machining titanium alloys, Oliaei and Karpat [17] found that the tailored micro-cutting tools with stable BUE helped increase the tool life. And three stronger peaks of Ti, Al, and V were identified in the location of the tool flank, indicating that the micro-mills occurred adhesive wear (Fig. 5). It is seen from Fig. 6 that a

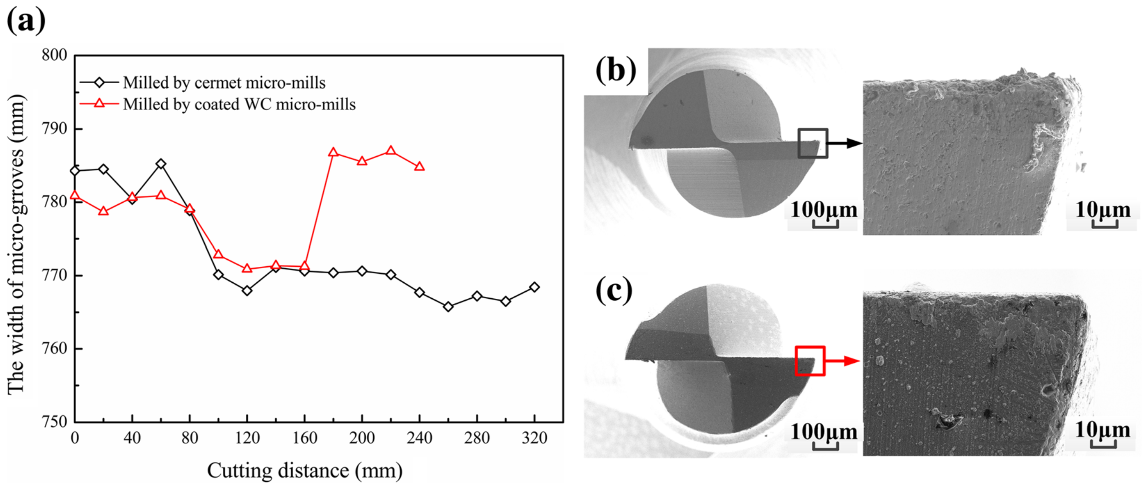
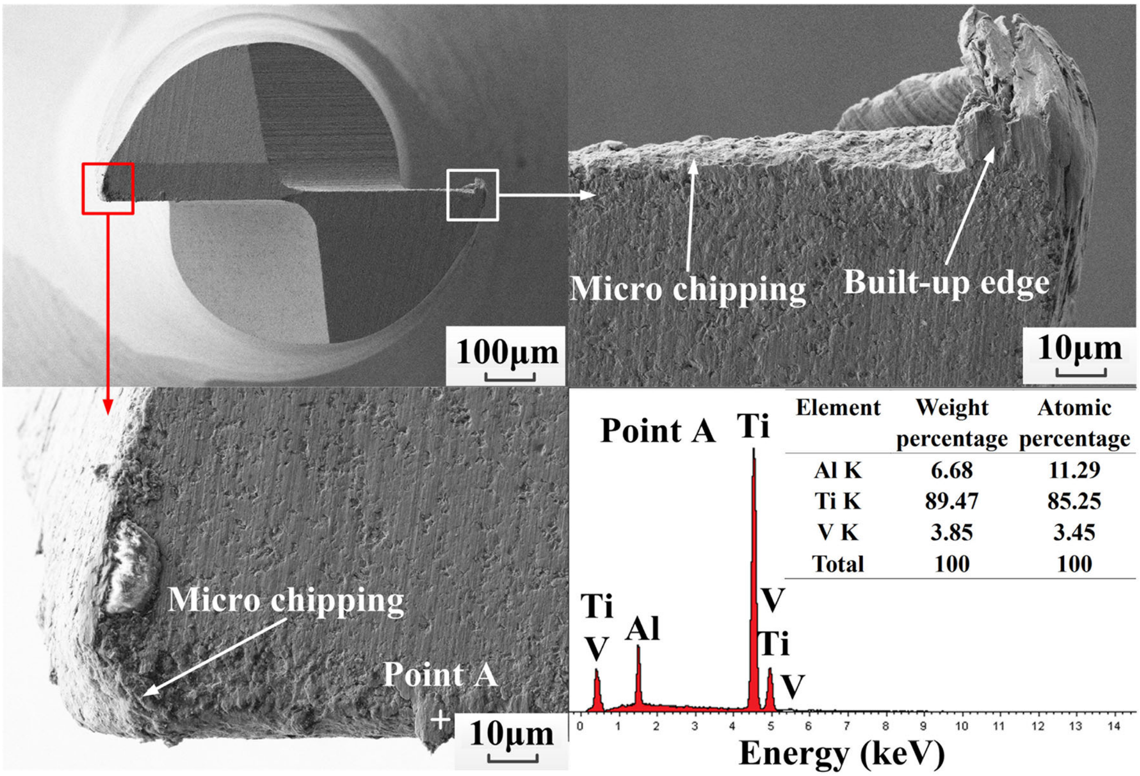


Fig. 4 **a** The milled micro-groove width variations using cermet and coated WC micro-mills. **b** SEM micrographs with the cutting distance of 83 mm using cermet micro-mills. **c** SEM micrographs with the cutting distance of 166 mm using coated WC micro-mills

BUE had fallen off the cutting edge, which led to a large chipping on the junction of the flank and the rake face at the machining of 332 mm. Cutting temperature could become serious in micromachining of TC4 alloy owning to its low thermal conductivity and high strength-to-weight ratio. It is undoubted that the increased cutting temperature and higher cutting forces can give a rise to stress concentration of cutting edge, and the crack can propagate, accumulate, and finally cause material to fracture once the stress impact is greater than the initial stress of crack. However, no fracture was observed for our developed cermet micro-mills during the whole machining. There was only a small amount of pull out of grains and micro-chipping occurring near the tool tip (Fig. 6), which was caused by the fatigue stress state of interrupt cutting. The theoretical fatigue life of our developed cermet micro-mills could be 12 min [5].

To compare with cermet micro-mills, Figure 7 shows the SEM micrographs of tool wear of WC micro-mills in machining of titanium alloy. The main wear patterns included the adhesive wear, micro-chipping, BUE, and flank wear, and



Element	Weight percentage	Atomic percentage
Al K	6.68	11.29
Ti K	89.47	85.25
V K	3.85	3.45
Total	100	100

Fig. 5 SEM micrographs and EDS of wear morphologies on cermet micro-mills machining after a distance of 166 mm

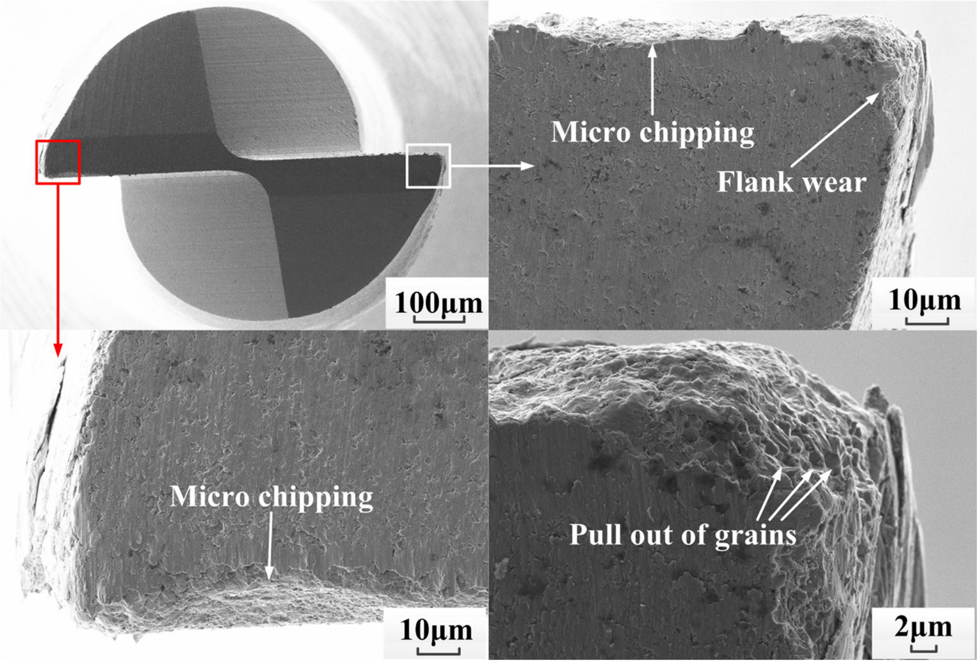


Fig. 6 SEM micrographs wear morphologies on cermet micro-mills machining after a distance of 332 mm

the micro-chipping reached a few tens of microns. Many grinding marks and cavities caused by grinding on the new coated WC micro-mill were found (see Fig. 1), which can also be seen in Fig. 7. However, the cermet micro-milling tool has a good surface quality. Grinding marks on flank face of WC micro-mills were found, which indicated a mechanical abrasive mechanism because of its relatively lower hardness than that of cermet micro-mills. These surface defects could lead a seriously stress concentration and weaken the tool stiffness, and could cause a bad surface quality of micro-grooves. Furthermore, multiple tool failure modes had occurred before the coated WC micro-mills were significantly worn out at machining of 83 mm (see Fig. 7a). As a matter of fact, one of the teeth of the coated WC micro-mills had broken at the machining distance of 249 mm, and its fracture size was measured to be 100 μm. Therefore, these analyses demonstrated that our developed cermet micro-mills could exhibit a longer tool life than commercial-coated WC micro-mills. During machining of the TC4 alloy, the shortcomings of coated WC micro-mills were attributed to delaminating and peeling off of the coating from the substrate as shown in Fig. 8b, c. It can be found that the coating of CrTiAlN had already began to peel off when the cutting distance was 83 mm. For coated WC-Co micro-milling tools, peeling off coating was prone to being followed by flank wear and fracture and eventually failed [18]. At the same time, the adhesive layer of TC4 alloy forming at rake and flank faces of micro-mills participated to machine instead of tool tip (Fig. 8c, d), which altered the

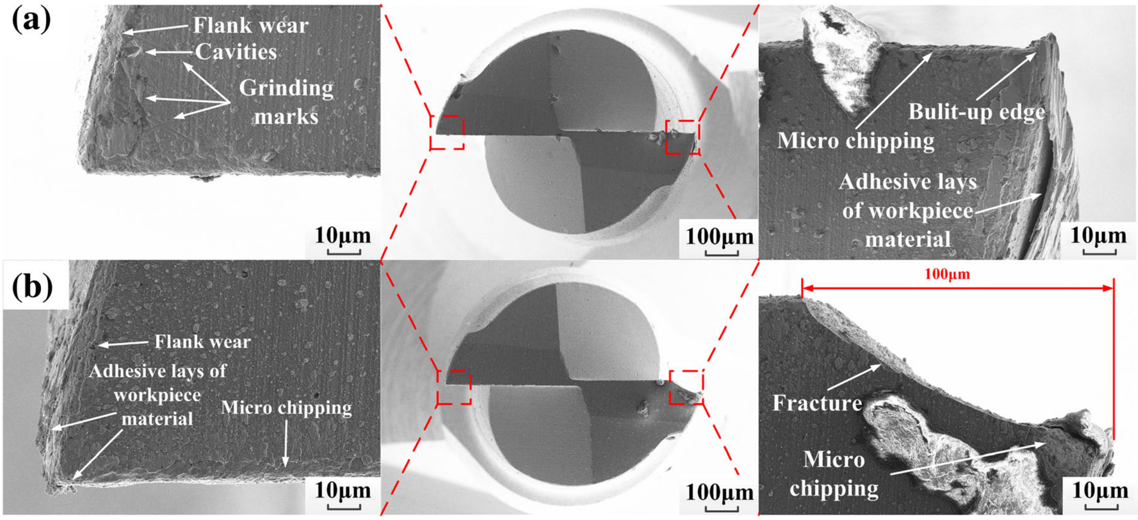
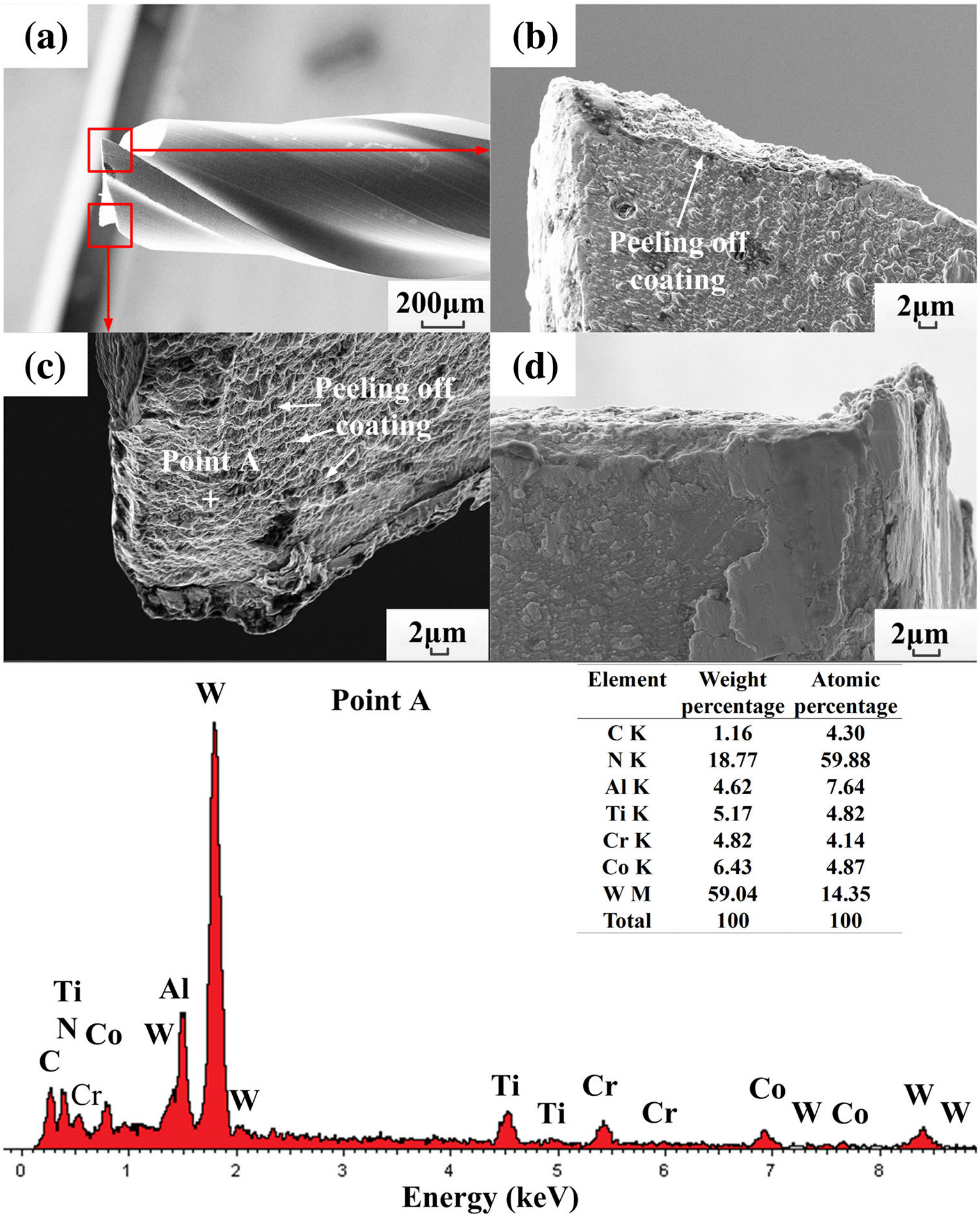


Fig. 7 SEM micrographs of wear morphologies on coated WC micro-mills after machining after a distance of **a** 83 mm and **b** 249 mm



Element	Weight percentage	Atomic percentage
C K	1.16	4.30
N K	18.77	59.88
Al K	4.62	7.64
Ti K	5.17	4.82
Cr K	4.82	4.14
Co K	6.43	4.87
W M	59.04	14.35
Total	100	100

Fig. 8 SEM and EDS micrographs representing the wear mechanism of coated WC micro-mills at a machining distance of 83 mm. **a** The cutting part. **b** One tool tip. **c** Another tool tip. **d** The bottom view of tool tip

physical properties of the tool material, such as the thermal conductivity, cutting edge radius, the hardness, and so on.

The larger edge radius of coated WC micro-mills contributed directly to the higher milling heat. Because the diameter of the micro-mill is small and high temperature locates in a small area near the tool tip, the tool wear is sensitive to cutting temperature. And Yang et al. (2011) also found the effective stress and mean cutting temperature of micro-mill was bound up with tool edge radius [19]. The machining parameters were cutting speed of 25.1 m/min, feed velocity of 0.005 mm/tooth, and depth of cutting of 0.1 mm, and the maximum temperature was 454 °C using a finite element model and experimental approaches in the micro-milling process of TC4 [20]. Thermal field plays a pivotal role in affecting micro-cutting performance because of centralized heat generation in a small area near the tool tip. Though the coating can protect the WC substrate from abrasion and adhesive wear, coated WC micro-mills would rapidly wear to fail once the coating was worn or peeled off. This phenomenon of rapid wear was non-existent because of the higher hardness of cermet than CrTiAlN coating. Thus, it can be inferred from the wear resistance and tool life that the milling performance of cermet micro-mills was superior to coated WC micro-mills.

3.2 Micro-milling force

Many works have thoroughly investigated the milling force characteristics of conventional machining, while the micro-milling forces are not yet fully understood because many factors in the macro and the micro multi-scale can affect the

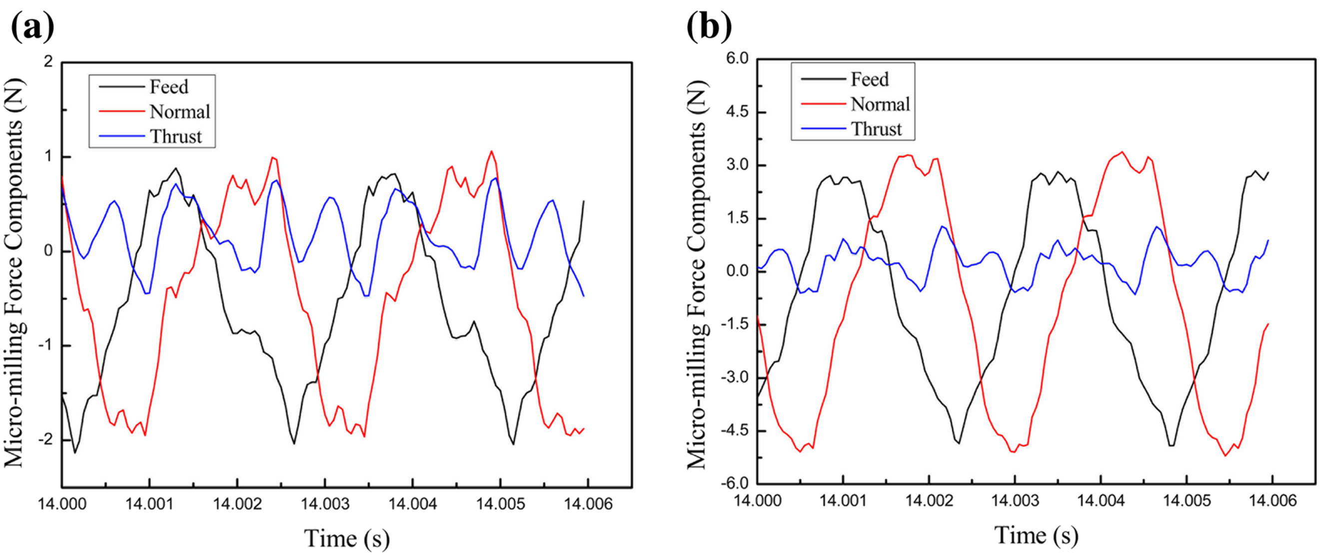


Fig. 9 The micro-milling force of **a** cermet micro-mills and **b** coated WC micro-mills in machining of Ti-6Al-4V alloy micro-grooves

cutting process, such as the runout of tool tip, chip thickness, plowing, indentation, and elastic recovery of workpiece [12]. To achieve an overall perspective of effects of tool wear on micro-milling forces, P-to-V feed and normal forces were collected and averaged over 100 revolutions. Figure 9 shows the micro-milling forces in machining of TC4 alloy micro-grooves using cermet and coated WC micro-mills, respectively. The periodicity with the tool-passing frequency was observed. However, micro-milling force signs for both of cermet and coated WC micro-mills were different from a sine function, and it contained micro-relaxations at both the ascent and decent portion. Figure 10 shows the variations in P-to-V feed and normal forces with the cutting distance. It was seen that the small increase in forces was experienced for cermet micro-mills with the cutting distance. However, both the P-to-V feed force and normal forces were much higher in the beginning of machining using the coated WC micro-mills. It is obviously seen that the feed and normal forces using the coated WC micro-mills were much higher than our developed cermet micro-mills. The higher hardness of cermet of our developed cermet material can ensure the edge radius of tool tip to be manufactured to 1.60–2.45 μm. Thus, our developed cermet micro-mills have a sharper edge radius than the coated WC micro-mills. Moreover, the cutting edge radius has the most significant effect on cutting force, and the cutting force increased with the increase of tool edge radius [19]. And Wu et al. [21] demonstrated that a sharp cutting edge could reduce the level of tool stress and tool temperature considerably. The smaller cutting forces of cermet micro-mills resulted from not only the smaller cutting edge radius but also the good wear resistance of micro-mills during the whole of machining. The good wear resistance of micro-mills can make the cutting edge

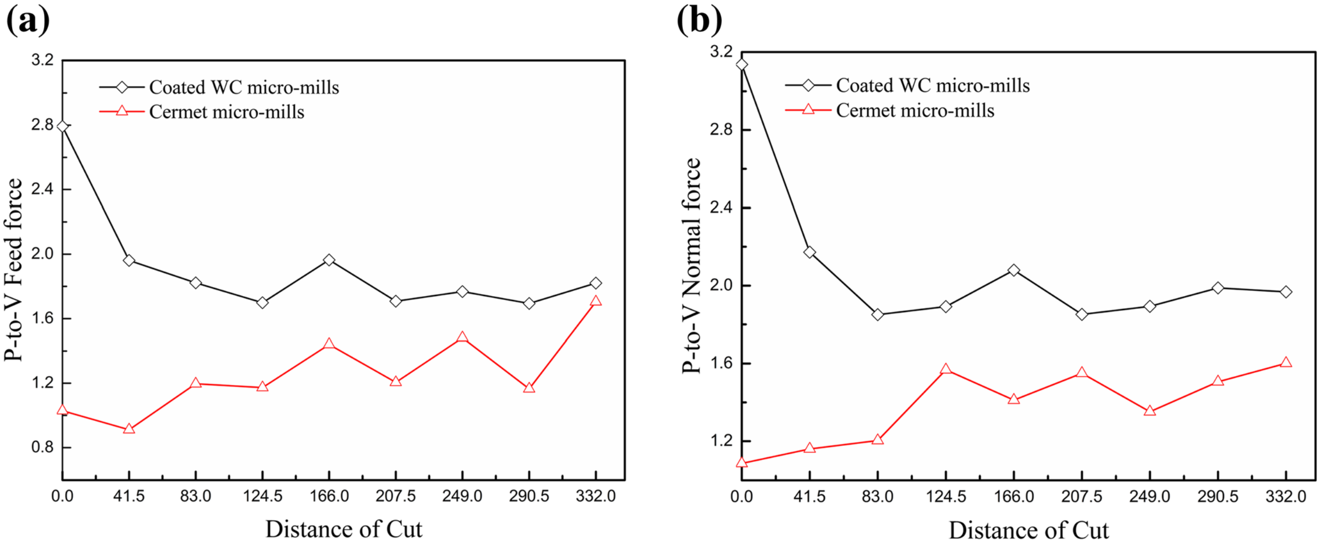


Fig. 10 The micro-milling force of **a** peak-to-valley feed force and **b** peak-to-valley normal force using cermet and coated WC micro-mills at the different cutting distances

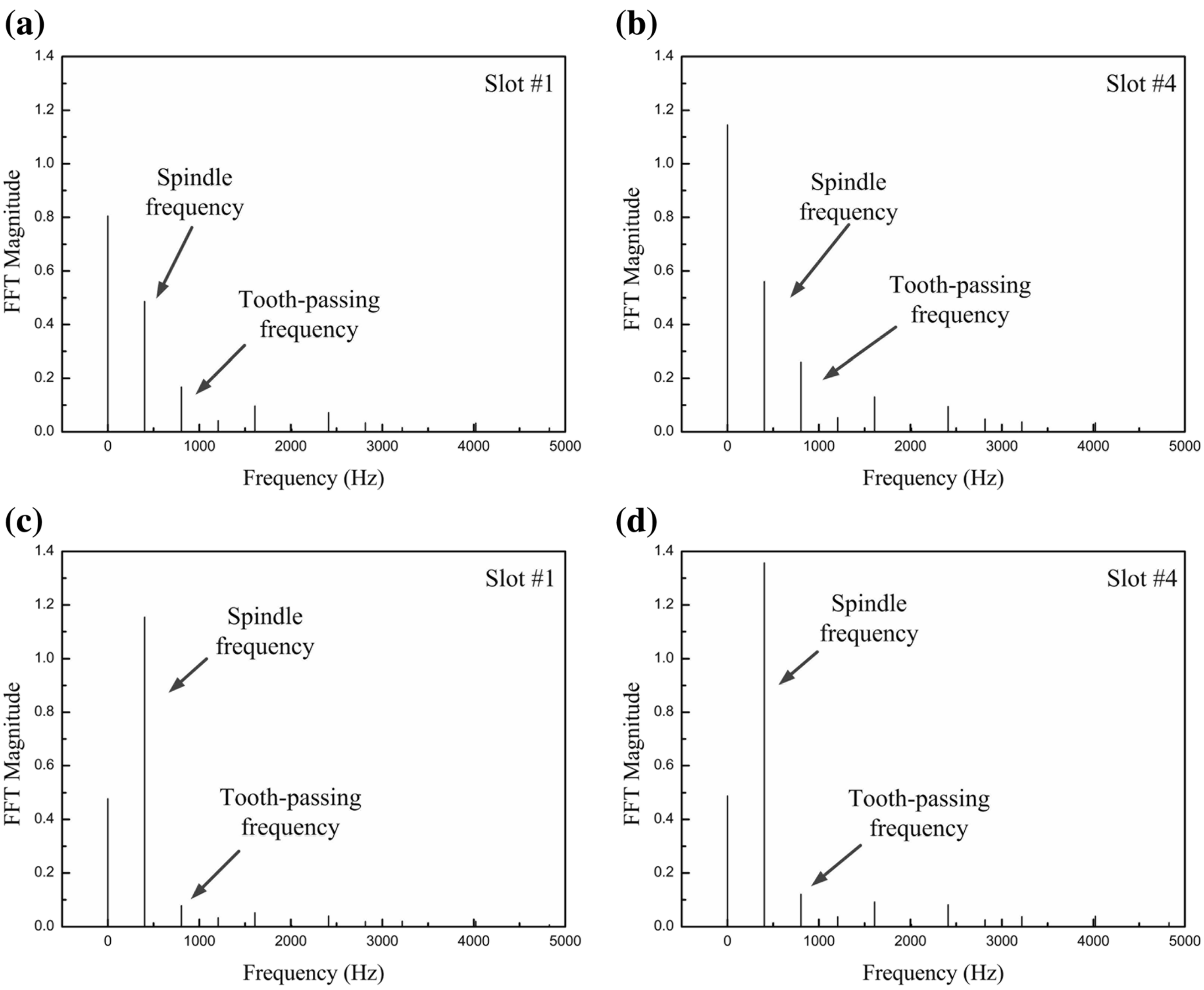


Fig. 11 Fast Fourier transform of the feed force of **a** and **b** cermet micro-mills and **c** and **d** coated WC micro-mills

keep the stable sharpness after milling at a distance of 332 mm. According to the AE signals during micro-milling of Ti-6Al-4V to determine the minimum chip thickness value, the result achieved the minimum chip thickness which was about 19~27.5% of the edge radius [22]. Because the mean edge radius of coated WC micro-mills was about 2.94–3.77 μm, the minimum chip thickness was in a range from 0.559 to 1.04 μm, with the result that higher values in both P-to-V feed forces and normal forces were achieved at about 0.001-mm/tooth feed rate using coated WC micro-mills because of the plowing effect. Figure 11 shows the fast Fourier transform (FFT) of the feed force, and the frequency components included the spindle and tooth-passing frequencies and its multiples. Compared with the FFT of the feed force of cermet micro-mills, the results of using coated WC micro-mills had a large peak at the spindle frequency of 402 Hz at the 1st and 4th slot, indicating a significant amount of tool-tip runout. The tool-tip runout can redistribute the chip load, and

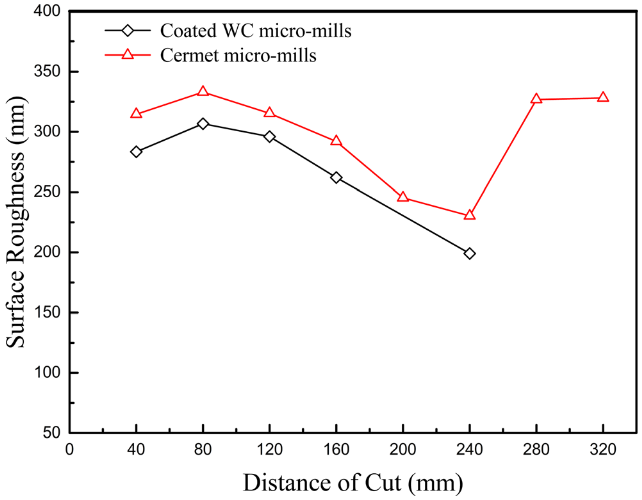


Fig. 12 Surface roughness of titanium alloy micro-groove at the different cutting distances

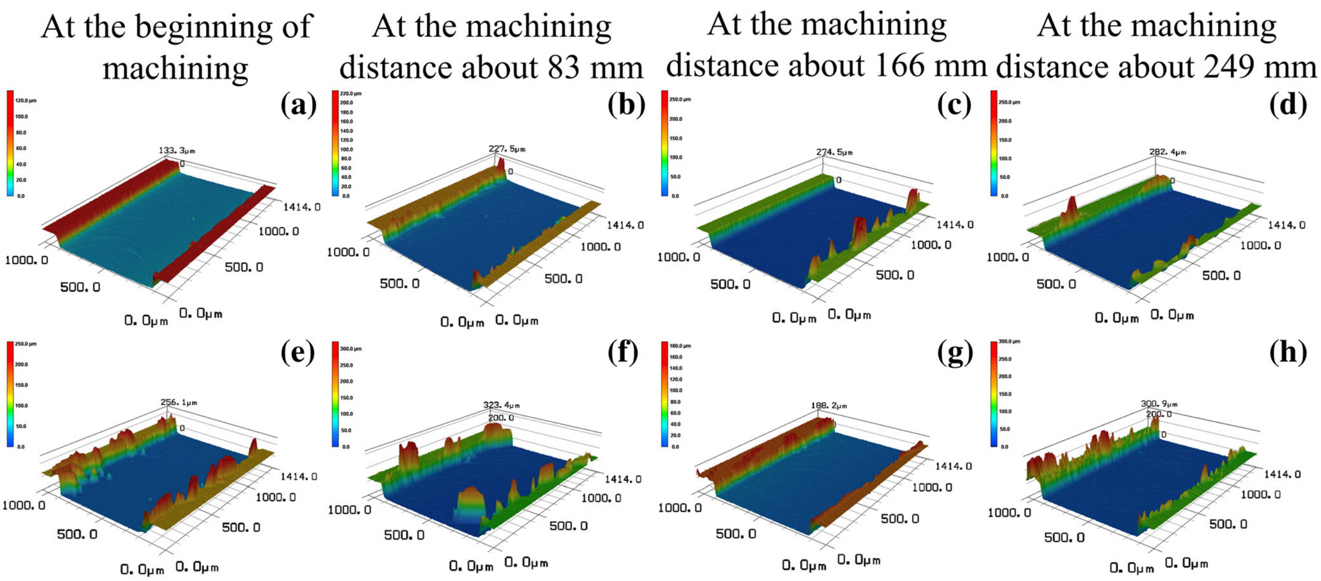


Fig. 13 3-D surface morphology of titanium alloy micro-grooves. **a**–**d** Micro-grooves were milled by cermet micro-mills. **e**–**h** Micro-grooves were milled by coated WC micro-mills

the uneven chip load will cause that one cutting flute takes more chip load than the other, and will also generate cutting forces with significant energy at the spindle frequency, which can cause tool wear rapidly [11].

3.3 Machined micro-groove quality

The surface roughness (Ra) of titanium alloy micro-grooves at the different cutting distance is shown in Fig. 12. It is seen that the surface roughness shows small variations with the increased cutting distance, and surface roughness of micro-grooves using cermet and coated WC micro-mills were very similar. For the two kinds of micro-mills, the surface roughness remained approximately constant up to 120 mm. However, a rapid reduction in surface roughness was observed with increased cutting length from 120 to 240 mm. Because the increased tool-tip radius due to tool wear can reduce the cusp height for same feed rate, resulting in lower roughness values [12]. Increasing the cutting distance from 240 to 320 mm using cermet micro-mills, the Ra value was shown upward trend. With the progress of micro-tool wear, the cutting edge radius of the micro-mills enlarged, which led to a

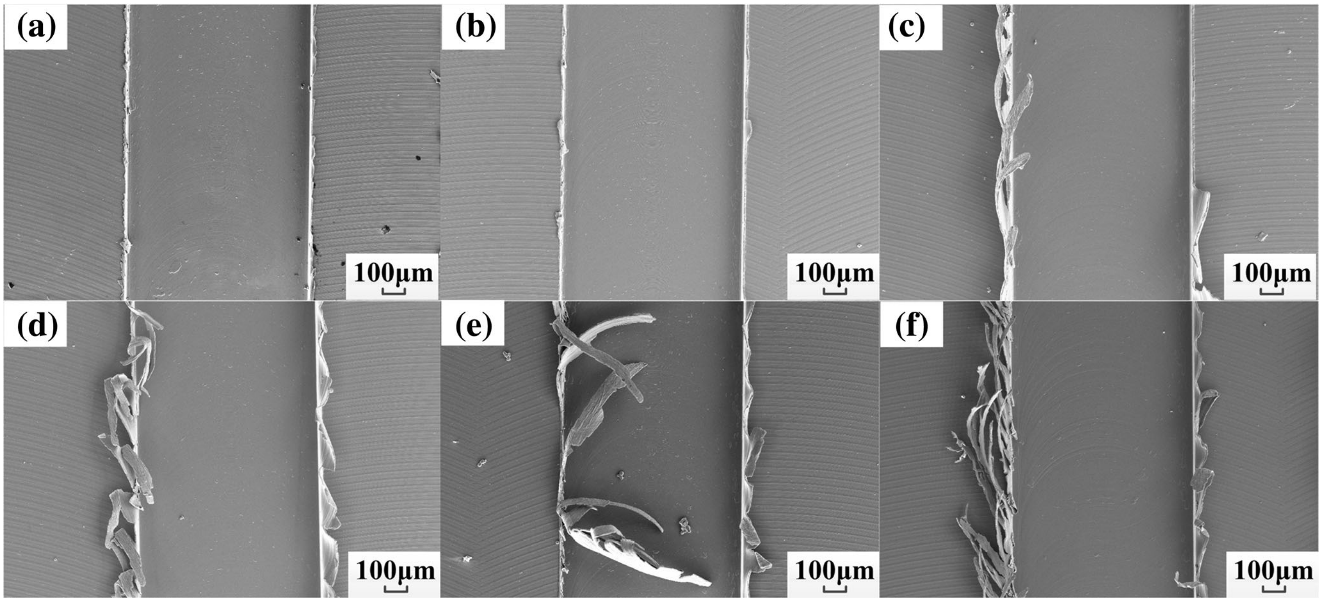


Fig. 14 Top view of SEM micrographs of titanium alloy micro-grooves: **a** and **d** were at the beginning of machining for cermet and coated WC micro-mills, respectively; **b** and **e** were a fragment of cutting distance between 83 and 166 mm for cermet and coated WC micro-mills, respectively; **c** and **f** were a fragment of cutting distance between 166 and 249 mm for cermet and coated WC micro-mills, respectively

larger negative rake angle in the machining. The negative rake angle induced elastic recovery of the machined surface and plowing effect. The surface roughness value increased when plowing occurred [23]. The surface roughness numerical difference between micro-grooves was very small, and the maximum difference was about 40 nm, and both of them could achieve a good surface roughness.

Figure 13 clearly shows the 3-D surface morphology of titanium alloy micro-grooves at particular cutting distance. The surface morphology of micro-grooves milled by cermet micro-mills had a higher precision in the whole machining, and it implied that the cermet micro-mills could easily remove TC4 alloy material and obtain excellent surface quality. However, massive top burrs remained along the top of slot walls milled by coated WC micro-mills and some of the burrs fell at the bottom of micro-grooves, leading to an undesired surface quality. The SEM micrographs of titanium alloy micro-grooves are shown in Fig. 14. The results indicated that the top burr was present during the entire machining using coated WC micro-mills, and burrs were observed at the beginning of machining and the size of them was comparable to that at cutting distance between 166 and 249 mm milled by cermet micro-mills (Fig. 14c, d). Because the larger cutting edge radius of coated WC micro-mills, lots of the deformed materials were not cut down in the cutting zone due to the plowing effect. It was also found that the top burr was long and narrow, and the size of burrs was almost the same with the width of micro-grooves (Fig. 14e). However, the top burrs were first found at the cutting distance of 12 mm using cermet micro-mills, and the size of burrs was relatively smaller. Given the above, cermet micro-mills could manufacture desired surface quality of micro-grooves in terms of surface roughness and burr formation compared with coated WC micro-mills in machining of TC4 alloy.

4 Conclusions

Self-developed Ti(C_7N_3)-based cermet micro-mills with a diameter of 0.8 mm had the cutting edge radius ranging from 1.60 to 2.45 μm. The micro-cutting performance of cermet and coated WC micro-mills in machining of TC4 alloy micro-grooves in terms of tool damage, micro-milling forces, and surface quality was investigated:

(1) For the cermet micro-mills, the micro-groove width varied from 784 to about 768 μm. However, the width of the milled micro-grooves exhibited an unstable change for coated WC micro-mills. The wear mechanisms of cermet micro-mills were found to be adhesive wear, micro-chipping, flank wear, and BUE. Many grinding marks and cavities caused by grinding on the new coated WC micro-mill were found, and these surface defects could lead a seriously stress concentration and weaken the tool stiffness. One of the teeth of the coated WC micro-mills had broken in the machining, and its fracture size was measured to be 100 μm. These analyses demonstrate that our developed cermet micro-mills can exhibit a longer tool life than commercial-coated WC micro-mills.

(2) The P-to-V feed and normal forces using the coated WC micro-mills were much higher than our developed cermet micro-mills, and a significant amount of tool-tip runout existed when coated WC micro-mills were used.

(3) The surface roughness numerical difference between micro-grooves milled by cermet and coated WC micro-mills was very small, and both of them could achieve a good surface roughness. The top burrs were present during the entire machining using coated WC micro-mills. However, the top burrs were first found at the cutting distance of 12 mm using cermet micro-mills, and the size of burr was relatively smaller.

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