The International Journal of Advanced Manufacturing Technology (2019) 102:2649–2661
https://doi.org/10.1007/s00170-018-3074-7

ORIGINAL ARTICLE

Machining performance of PCD and PCBN tools in dry turning titanium alloy Ti-6Al-0.6Cr-0.4Fe-0.4Si-0.01B

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Received: 15 May 2018 / Accepted: 19 November 2018 / Published online: 2 February 2019

Abstract
Titanium alloys are typical difficult-to-machine materials. The experiment is conducted by turning Ti-6Al-0.6Cr-0.4Fe-0.4Si-0.01B (TC7) with PCD and PCBN tools under dry condition. The paper focuses on studying the performance of PCD tools in dry turning TC7 and investigating the machinability of TC7. Wear mechanisms of two cutting tools are analyzed and compared by scanning electronic microscopic (SEM) images of worn inserts. The effect of cutting parameters (cutting speed, feed rate and depth of cut) on tool life is studied by measuring the average flank wear with 3D super-depth-of-field instrument. The influence of cutting parameters on cutting temperature, surface roughness, and surface microhardness is also investigated. The results show that although non-uniform wear band forms on both tools of PCD and PCBN, the wear of PCBN is serious than that of PCD. The adhesion-dissolution-diffusion mechanism takes effect on two tools during machining. For PCD tool, obvious adhesion and chipping occur. For PCBN tool, adhesion, notching, and crater occur. The main conclusion is that PCD tool has better performance than PCBN tool. PCD tool is suitable for machining TC7. The machinability of TC7 is poorer than that of TC4. The hardening of workpiece surface layer occurs.

Keywords Titanium alloy · Dry machining · PCD · PCBN · Wear mechanism

1 Introduction

Titanium and titanium alloys have been extensively utilized in aerospace, automotive, biomedical, and petroleum industries due to an outstanding combination of properties, such as high strength at elevated temperature and low density, and so on [1]. However, titanium and its alloys are commonly considered as difficult-to-machine materials [2, 3]. During the machining of titanium alloys, the wear rate of cutting tools is high, owing to high strength, low thermal conductivity, and high chemical reactivity [4, 5]. Coating delamination, adhesion, attrition, diffusion, plastic deformation, chemical reaction, crater, and cracks occur during machining of titanium alloys, which deteriorates the machinability and the workpiece surface roughness [6–8].

The cutting speed is lower during machining titanium alloys. So many efforts focus on tool materials selection and performance comparison of different cutting tools, such as high speed steel, tungsten carbide (WC), polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN), and so on. It is reported that the cutting speed in machining titanium alloys Ti-6Al-4V (TC4) with high-speed steel (HSS) tools is below 30 m/min, while with tungsten carbide (WC) tools, it is below 60 m/min [9]. Although these cutting tools are economical, the low cutting speed leads to low productivity. Among various ultra-hard cutting tools, PCD tool shows better tool life, machining quality, and so on [10]. Further study shows that PCD tools possess lower wear rate and excellent performance during machining TC4, while PCBN tools have higher wear rate and poor

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Table 1 Chemical composition of the titanium alloy TC7

element	Al	Ti	Cr	Fe	Si	B	C	H	O	N
wt%	5.29	89.28	0.60	0.38	0.31	0.011	0.005	< 0.001	0.053	0.006

performance [11, 12]. According to Ezugwu [12], PCBN/CBN tools are not recommended for machining titanium alloys.

The wear mechanisms of PCD and PCBN are investigated. It is reported that forms of tool wear depend on the cutting temperature during machining titanium alloy with CBN tool [4]. At lower cutting speed (low temperature), the wear is localized chipping of the cutting edge and wide crater on the rake face. With the increase of cutting speed, deep crater and tool nose wear occur. At higher cutting temperature of 1100 °C, titanium compound occurs, revealing that diffusion wear takes place due to reaction between the titanium alloy and tool material. According to Zoya, et al. [4], 700 °C is a critical temperature for the presence of diffusion wear. The turning of TC4 with three types of PCD inserts shows that the main wear mechanisms are chipping, adhesion, diffusion, and crater wear [9]. The study also indicates that the tool wear is sensitive to cutting temperature because the hardness of PCD tool reduces at high cutting temperature.

Tool life and surface integrity are of great importance for machining titanium alloys. During dry machining titanium alloy TA48, the wear rate of PCD tools keeps stable even after 30 min and that of PCBN tools increases rapidly within 11 min [13]. The similar results are found about surface roughness. It is found that the higher cutting speed and lower feed rate are more optimal cutting parameters for prolongation of service life of CBN tools [14]. PCD tools have better wear resistance and higher cutting speed than cemented carbide tools [15]. PCD tools generate a clean-cut surface without damage while cemented carbide tools produce a relative clean-cut surface with extending damage. The surface morphology and sub-surface microhardness are studied, revealing that the hardened layer forms and the depth increases with increase of cutting speed [16].

In order to solve these problems and improve the machinability, many technologies are developed, such as high-pressure coolant, cryogenic cooling, minimum quantity cooled lubrication (MQCL), and so on. These technologies increase the tool life, decrease the cutting temperature, and improve the machining quality [17–19]. However, it is reported that the careless utilization of liquid nitrogen and carbon dioxide snow can cause cold burns and asphyxiation to workers [20]. It is also showed that cutting fluids are complex petroleum/chemical compounds, which can cause skin and lung disorders and is harmful to environment and health [21, 22]. The quality of cutting fluid deteriorates and the harm accumulates [23]. In short, these cutting fluids need special management, such as handling, transportation, treatment, and disposal, which increases the cost of manufacturing. Recently, dry machining of titanium without any coolant has been drawing increasing attention [24]. However, dry machining means a great challenge to machining titanium alloy because the absence of cutting fluids results in high friction and high cutting temperature at the tool-workpiece interface. This will decrease the tool life and accelerate tool wear [25]. Many studies focus on tool material selection and understanding the wear mechanism of cutting tools in dry machining [26, 27].

Titanium alloy TC7 has excellent mechanical properties, such as higher tensile strength and lower yield strength, which means that its plasticity and strength is better than TC4. TC7 has better fatigue resistance due to its colonies microstructure. So TC7 is often used as material for shaft, frame and joint in large equipment, which bears great force. The machined surface should possess low surface roughness. However, TC7 is a kind of difficult-to-machine material and there are few published studies about it. The novelty of the paper is to study the performance of PCD tools in dry turning TC7 and to investigate machinability of TC7. The wear mechanisms and tool life of both tools are investigated and compared in detail. The effect of parameters on cutting temperature, surface roughness, and microhardness of surface layer is investigated.

2 Experimental procedures

2.1 Workpiece material

The workpiece material is titanium alloy TC7. It is a round bar with diameter of 100 mm and length of 500 mm. The chemical

Table 2 Comparison of mechanical properties of the titanium alloy TC7 and TC4 [7]

	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of cross-section area (%)	Elastic modulus (GPa)	Poisson's ratio	Microhardness(HV)
TC7	810	910	12.8	30	113.7	0.296	360
TC4	828	895	10	25	112.5	0.31	/

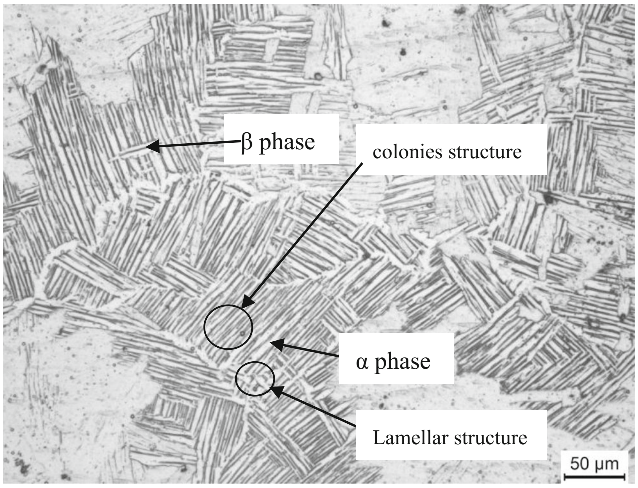


Fig. 1 Microstructure of TC7 workpiece material

compositions and mechanical properties are shown in Tables 1 and 2, respectively. From Table 2, it can be seen that the yield strength of TC7 is lower than that of TC4, while its tensile strength is higher than that of TC4.

A cube with side length of 10 mm was cut from the workpiece by electrical discharge machining (EDM). After ground with SiC abrasive paper from 360 to 3000 grit and polished, the specimen was etched by Kroll's reagent (6.5% HF + 15.6% HNO_3 + 77.9% H_2O) for 10 s to acquire the microstructure. The microstructure was observed with a LEICA CTR4000 optical microscope (Leica, Weitzlal, Germany). The image of microstructure is shown in Fig. 1.

2.2 Cutting tool

PCD and PCBN tools were employed in the experiments and the both types were CNGA120404 (JCCT Co., LTD, Foshan, China). Cemented tungsten carbide (wt. 8% Co) was adopted as substrate material of the tool. The PCD and PCBN inserts were embedded in the tool substrate. PCD insert's microhardness is 7000HV, PCBN, 3200–3500HV. PCD has medium grain and PCBN has refine grain. Additionally, the PCBN material consisted of 90 wt% cubic boron nitride (CBN) and 10 wt% Al + Ni + Co as a metallic binder. The specification of tool holder was MCLNR2020K12C (ZCCCT Co., LTD, Zhuzhou, China). The geometrical parameters of combination of insert fixed in tool holder are shown in Table 3.

2.3 Equipment and methodology

The dry turning experiments were carried out on a CNC CA6150i lathe (DMTG Co., China) under dry condition without lubricant and coolant. A RC 10+ handheld infrared thermal imager (Rinch, HK, China) was used to characterize cutting temperature. A single-factor experiment was carried out, and one test was done for each set. For each group of cutting parameters, thermal imager was set to take photos every 2 s. Simultaneously, thermal imager displayed and saved every photo's highest temperate. The highest temperature in the all photos of this group of cutting parameters was selected as the cutting temperature for this group of cutting parameters itself. For the same cutting parameter, every insert was taken down from the tool holder after the workpiece was machined for 3, 6, 9, 12, 15 min, respectively. Then, the inserts were cleaned in alcohol (99%) by ultrasonic for 6 min. The wear morphologies and surface chemical compositions of inserts were characterized by scanning electron microscope (SEM, Quanta 200 FEG, FEI, Eindhoven, Netherlands) and energy-dispersive spectrometer (EDS), respectively. A VHX-600E-3D (Keyence, Osaka, Japan) super-depth-of-field instrument was used to measure average flank wear width (VB) of inserts according to standard of ISO 3685:1993. The surface roughness of workpiece after machined was measured with MarSurf M 300C (Mahr GmbH, Göttingen, Germany) surface profile instrument. For each cutting parameter (for instance, cutting speed of 30 m/min), six points were tested along the circle of machined cylindrical surface at equal intervals to get six surface roughness values, then the results was averaged as this cutting parameters' surface roughness. The workpiece was cut perpendicular to the axis of itself by EDM and then the cross section was ground with SiC abrasive paper from 360 to 3000 grit and polished in order to measure the microhardness. The microhardness of the machined workpiece surface layer was measured with a MVS1000D1 (Guangjing, Guangzhou, China) microhardness tester. The microhardness was tested on the cross section along the radial direction from surface to substrate at interval of 0.05 mm. The chip was embedded in denture base material, then the inlay was ground with SiC abrasive paper from 360 to 3000 grit and polished. The chip cross section was observed with a LEICA CTR4000

Table 3 Geometrical parameters of insert fixed in tool holder

Rake angle	Relief angle	Cutting edge angle	Minor cutting edge angle	Nose radius
− 10°	5°	95°	5°	0.4 mm

Table 4 Input cutting parameters and output experiment results obtained in machining TC7

Input cutting parameters		Output experiment results of PCBN and PCD
Cutting speed (m/min)	PCBN: 30, 40, 50, 60	Average flank wear width (VB, mm);
	PCD: 40, 60, 80, 100	Roughness (μm);
Feed Rate (mm/r)	PCBN: 0.05, 0.1, 0.125, 0.15	Microhardness (HV);
	PCD: 0.05, 0.1, 0.125, 0.15	Cutting temperature (°C);
Depth of cut (mm)	PCBN: 0.5, 0.75,1.0, 1.25	
	PCD: 0.5, 0.75,1.0, 1.25, 1.5	
Criterion for stopping trials: VB = 0.3 mm.		

optical microscope. The input cutting parameters and output experiment results are shown in Table 4.

3 Results and discussions

3.1 Wear mechanism of the tool

3.1.1 Flank face wear

Figures 2 and 3 show the SEM images of flank faces of PCD and PCBN tools, respectively. It is observed that non-uniform wear at the flank face dominates two tools under all conditions of machining. The high cutting temperature at the cutting zone enhances the chemical reactivity and affinity of titanium alloys, close contact between tool and workpiece exists at the cutting zone. The EDS analysis demonstrates that point A contains approximately 40 wt% carbon and 50 wt% titanium, which reveals that the carbon element diffuses across the adherent layer and may produce the titanium carbide layer at tool/workpiece interface. The cutting force is high and the stress inside cutting tool is dynamic due to the serrated chips when machining titanium alloys [3]. The adhered materials are scratched from cutting tool due to the severe rubbing and dynamic cutting force between tool and workpiece, so notch wear forms (point C). This is different to study of Li, et al. [9], in which PCD tools suffer from abrasive wear due to hard particles.

The elements of cutting tool such as Co elements, and so on, diffuse into the adherent layer, which weakens the strength of cutting tool itself [28]. When adherent materials are flaked from cutting tool, cutting tool materials, such as WC and diamond particles are exposed and tool wear is accelerated (point B). And the EDS analysis shows that about 8.9 wt% oxygen element exists on point B, indicating that oxidation reaction occurs during cutting.

It can be seen from Fig. 3b that workpiece materials adhere to cutting tool. The adherent layer is abraded by the workpiece and slight marks forms on the tool, which indicates that notch wear is occurring. It can be seen from Fig. 3c that cutting edge fractures and materials of workpiece deposit on worn cutting tool. During the cutting, the cutting forces are high and vary with the serrated chip, the stress imposed on the cutting edge fluctuates correspondingly [14]. Under condition of changing stress, the cutting edge is prone to crack.

The notch wear of PCBN tool occurs in high-speed milling of TA15, which is ascribed to the high cutting temperature, high cyclic stress, and the adhesion of titanium workpiece onto PCBN tool [1]. However, notch wear in present study is more severe than that in high-speed milling of TA15 because it can be observed that several places of notch wear forms in present study, while one place in the latter. The reason may lie in that TC7 is more difficult-to-machine than TA15 due to different mechanical properties of TC7 and TA15. For the same reason, the notch wear of PCD tool in machining TC7 is more severe than that of machining TA15.

3.1.2 Rake face wear

Figures 4 and 5 show the SEM images of rake faces of PCBN and PCD tools, respectively. Adhesive wear takes place on the rake faces of two tools. By comparison point A in Figs. 4b and

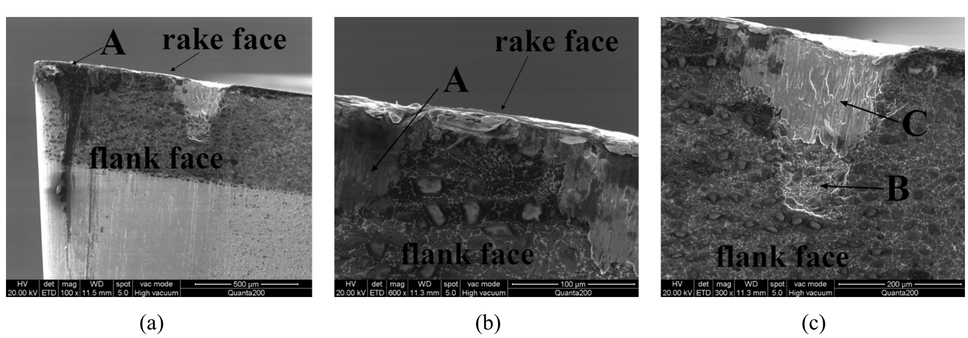


Fig. 2 SEM images of flank faces of PCD tools (cutting speed 40 m/min, feed rate 0.1 mm/r, depth of cut 1.0 mm, cutting time 6 min): **a** the flank face; **b** magnification of point A; **c** notch and flaking

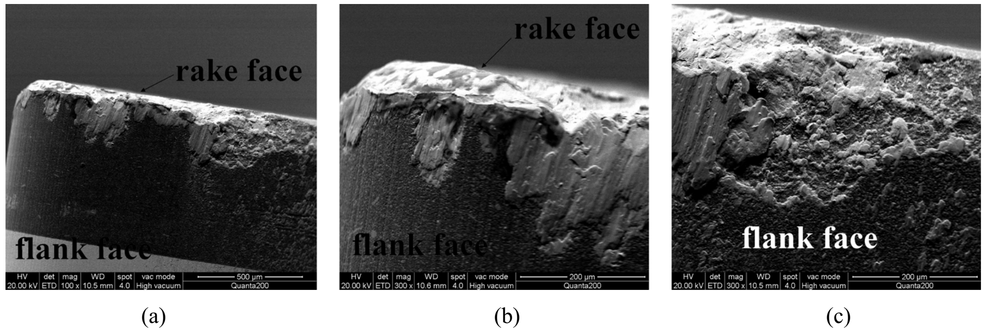


Fig. 3 SEM images of flank faces of PCBN tools (cutting speed 30 m/min, feed rate 0.1 mm/r, depth of cut: 1.0 mm, cutting time 6 min) **a** the flank face; **b** magnification of tool nose; **c** fracture

5b, it can make a conclusion that adhesive wear is more severe for PCBN tools. In Fig. 5b, it is apparent that the chip adheres onto the rake face. The main reason is that high cutting temperature causes high chemical activity and affinity of titanium alloy. The high cutting temperature and intimate contact at small cutting zone between tool and workpiece provide an ideal environment for diffusion through diffusion/dissolution mechanism. As a result, for CBN tool, Nitrides, borides, carbides, and oxides of elements form on the rake face during machining. For PCD tool, a titanium carbide layer occurs [29]. The adhesion of workpiece on the rake face is more serious in machining TC4 with PCD tool [30]. Accordingly, crater wear is more serious. The EDS analysis shows that in Fig. 4b, the point B on the tool nose of PCD contains 7 wt% oxygen and 48 wt% titanium approximately, which is the evidence of oxidation and diffusion. For PCBN tool, there is about 39 wt% titanium at point A in Fig. 5b, indicating that diffusion wear takes place. It is reported that the adhesion and chipping of PCD are very slight in dry machining TC4, which proves that cutting temperature plays an important role in the wear of PCD tool and TC7 is more difficult to machine than TC4 [10].

The adherent layer can protect cutting edge from further abrasion. However, adherent layer is unstable. It is abraded and torn by chips. Or as the stress reaches a higher level, it is detached from the tool. Then, the adherent layer is removed and hard particles are plucked out from the tool materials, which results in crater wear on the rake face [9]. In present study, slight crater is observed on the PCD tool but serious grooves and extensive craters are discovered on PCBN tool. The reasons may lie in that better wear resistance of adherent layer and strong adhesive forces between adherent layer and PCD tool materials. For PCBN tool, a phase change from CNB phase into HBN phase happened. The new phase has weaker mechanical properties and can be worn off easily compared to the PCD tool during machining [30]. It is reported that crater forms on the rake face of PCBN tool under the similar condition, but it is more slighter than the crater in present study [29]. It seems that no oxidation took place at the crater. As shown in Figs. 4c and 5c, fracture takes place on both tools, but it is more severe for PCBN tool.

3.2 Influence of cutting parameters on tool life

Before studying the influence of cutting parameters on the tool life, the standard ISO 3685:1993 should be noticed. In the standard, VB_{max} (the maximum flank wear) and VB (average flank wear) are stipulated as the end of useful tool life, which is equal to 0.6 mm and 0.3 mm, respectively. VB = 0.3 mm (average flank wear) is chosen in the present study.

3.2.1 Influence of cutting speed

Figure 6a, b shows the evolution of average flank wear VB versus cutting time at different cutting speeds during machining titanium alloy TC7 with PCD and PCBN tools,

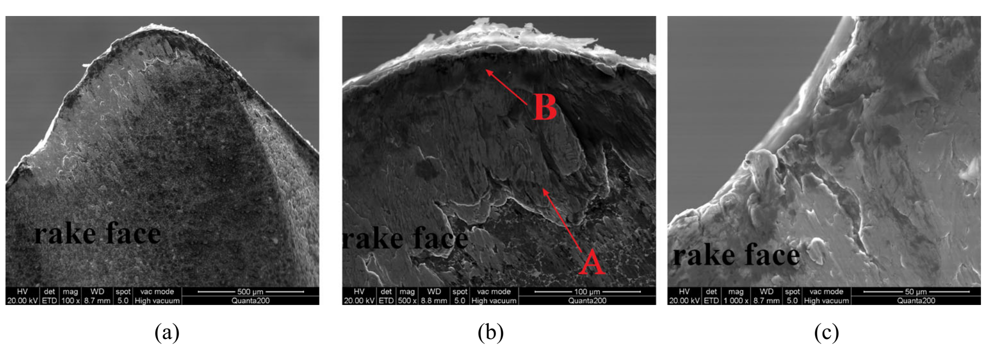


Fig. 4 SEM images of rake faces of PCD tools (cutting speed 40 m/min, feed rate 0.1 mm/r, depth of cut 1.0 mm, cutting time 6 min): **a** the rake face; **b** magnification of tool nose; **c** fracture

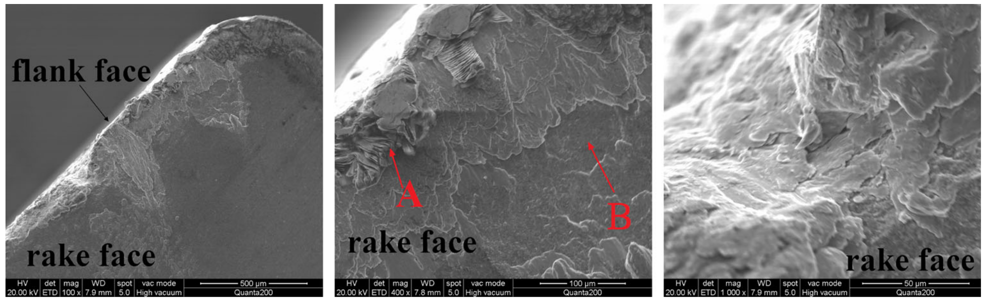


Fig. 5 SEM images of rake faces of PCBN tools (cutting speed 40 m/min, feed rate 0.1 mm/r, depth of cut 1.0 mm, cutting time 6 min): **a** the rake face; **b** magnification main cutting edge near tool nose; **c** fracture

respectively. For both tools, the wear is initially high and then keeps steady with the increasing of cutting time. For PCD tools, the average flank wear increases slowly after 3 min at cutting speed of 40 m/min. However, at cutting speed of 80 m/min, the average flank wear grows sharply all the time. It should be noted that the time for the sudden increasing in temperature depends on the cutting speed [4]. The tool life generally decreases with increasing of cutting speed because increasing of cutting speed reduces the length of tool-chip contact, which promotes the cutting temperature [31]. At the same time, both normal and shear stresses at the tool tip-cutting region increase. The promoting of cutting temperature induces the decrease of tool life and the failure of tool.

From Fig. 6, it is observed that the ranger of cutting speed with PCD tools is higher than that with PCBN tools in general. At the same cutting speed, for instance, 40 and 60 m/min, the wear of PCD tools is much lower than that of PCBN tools. The temperature of machining titanium alloys is very high, while the hot hardness of PCBN is lower than that of PCD at high temperature [12]. This can result in higher wear of PCBN tools. It can be also made a conclusion that VB increases linearly at all cutting speeds for PCD and PCBN tools in present study. This is different to exponential increase of VB in machining of TC4 with PCD tool [3].

3.2.2 Influence of feed rate

Figure 7a, b shows the progression of average flank wear VB versus cutting time at different feed rate during machining titanium alloy TC7 with PCD and PCBN tools, respectively. With the increase of feed rate, the VB of the both tools increases. The life of the PCD tools is longer than that of PCBN tools at the feed rate of 0.05 mm/r and 0.1 mm/r. However, the life of PCD tools becomes very short as the feed rate grows to 0.125 mm/r and 0.15 mm/r. At the feed rate of 0.125 mm/r, the inserts of PCD tools drop from the tool body about 2.2 min. At the feed rate of 0.2 mm/r, inserts fracture in the beginning. It has been reported by Astakhov [32] that as the feed rate increased, the tool squeezed and rubbed the workpiece strongly, which caused severe friction and great cutting force between the tool and the workpiece. Therefore, the wear of tools accelerates when the feed rate increases. According to Çelik, et al. [7], the tools wear bases on the cutting temperature. High cutting temperature promotes the process of adhesion–dissolution–diffusion and causes the adhesive wear, crater wear and notch wear, which speeds up the wear rate of tool [7, 33]. In the dry turning of TA48 at a surface speed of 75 m/min, a feed rate of 0.25 mm/r and a depth of cut of 1.0 mm, VB reaches 0.5 mm after 4 and 11 min for PCBN and PCD tools, respectively. However, the cutting tools fail quickly when feed rate

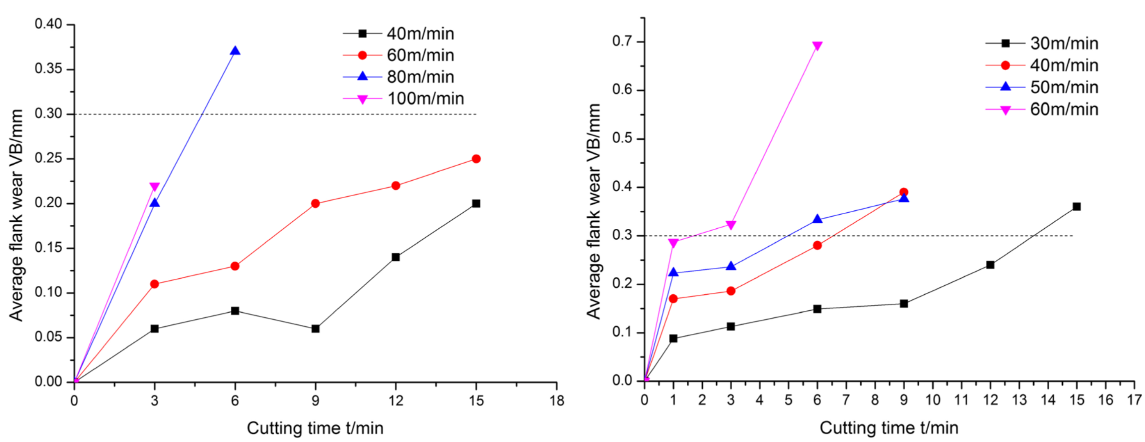
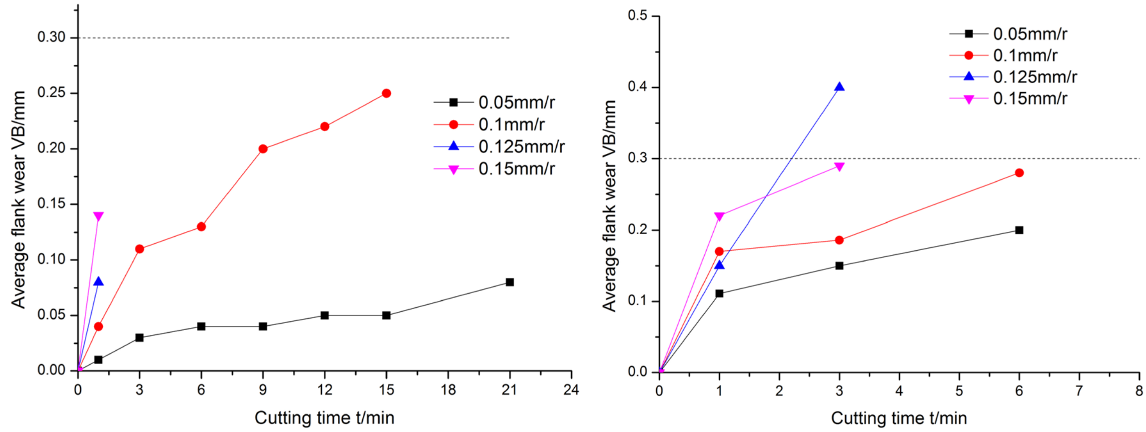


Fig. 6 Evolution of VB against cutting time at different cutting speeds with PCD tools and PCBN tools (feed rate 0.10 mm/r, depth of cut 1.0 mm)



(a) PCD tools (b) PCBN tools

Fig. 7 Evolution of VB against cutting time at different feed rate with PCD tools and PCBN tools (cutting speed for PCD tools, 60 m/min; for PCBN tools, 40 m/min, depth of cut for both tools, 1.0 mm)

exceeds 0.15 mm/r in present study. From this point of view, it can be made a conclusion that the machinability of TC7 is poorer than that of TA48 [13].

3.2.3 Influence of the depth of cut

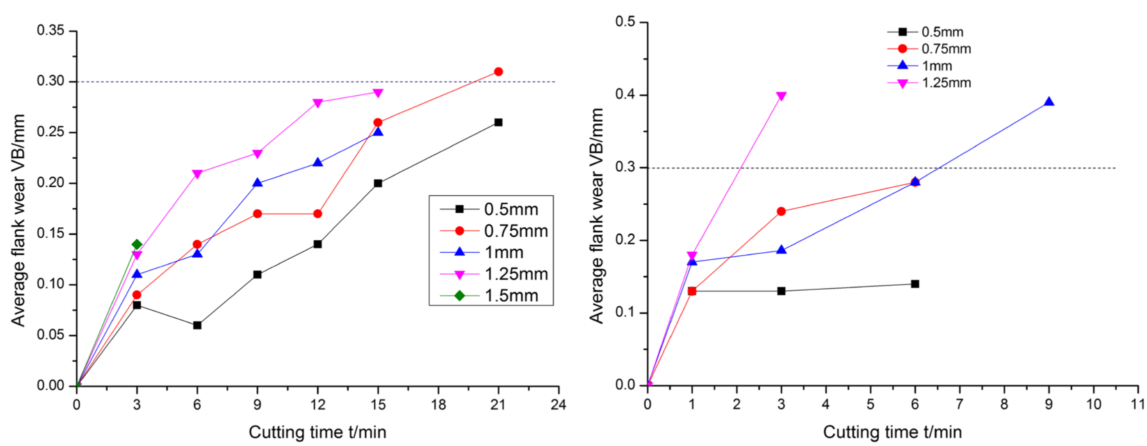
Figure 8a, b shows the progression of average flank wear VB versus cutting time at different depth of cut during machining titanium alloy TC7 with PCD and PCBN tools, respectively. The wear of both tools increases with the increase of depth of cut. It is indicated that an increase in the depth of cut does not change the tool wear rate because the average contact temperature remains unchanged due to the specific contact stresses at the tool–chip interfaces and the chip compression ratio (defined as the radio of the chip and the uncut chip thicknesses) remains unchanged [32]. For high depth of cut of 1.5 mm, the PCBN tools fracture when machining for about 5 min.

It can be made a conclusion that the PCD tools have better characteristics, such as better resistance to crater, better fracture toughness of cutting edge, and longer life, compared to PCBN tools. PCD tool is more suitable to machine the titanium alloy and PCBN tool is not suitable for machining titanium alloy. It can be also made a conclusion that titanium alloy TC7 has poorer machinability than titanium alloy TC4. The following study will focus on the PCD tool and PCBN tool is not discussed.

3.3 Influence of cutting parameters on cutting temperature using PCD tools

3.3.1 Influence of cutting speed

Figure 9 shows the evolution of cutting temperature against cutting speed with PCD tools. Although more chips carry away more heat, the cutting temperature



(a) PCD tools (b) PCBN tools

Fig. 8 Evolution of VB against cutting time at different depth of cut with PCD tools and PCBN tools (cutting speed for PCD tools, 60 m/min; for PCBN tools, 40 m/min, feed rate for both tools, 0.10 mm/r)

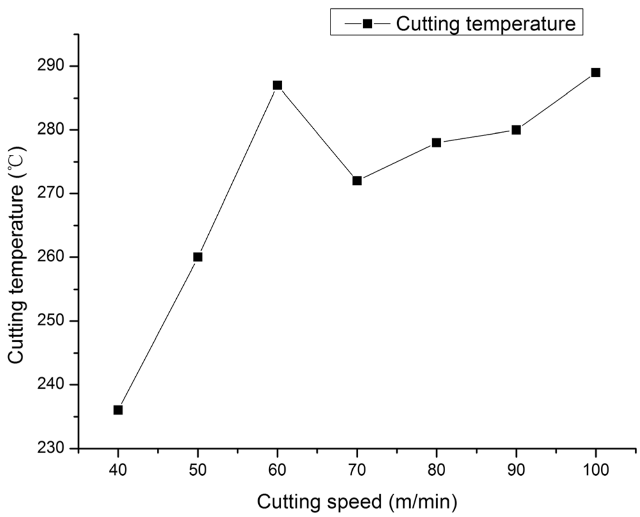


Fig. 9 Evolution of cutting temperature against cutting time at different cutting speed with PCD tools (feed rate 0.1 mm/r, depth of cut 1.0 mm)

increases with the increase of cutting speed because more heat is generated during machining than the heat carried away [34]. The adhered material of workpiece even the built-up layer fractures and drops from the cutting tool, which weakens the friction between the tool and workpiece and diminishes the heat generated at the cutting zone. So, cutting temperature decreases a little at cutting speed of 70 m/min. Infrared thermal imaging camera (specification: R300 Inf Rec) is used to measure the cutting temperature in the end milling of TC4, which shows that cutting temperature is between 200 and 300 °C and it increases with the increase of cutting speed, feed rate and depth of cut. Lower cutting temperature is obtained in present study due to high thermal conductivity of PCD insert compared to carbide tools [10].

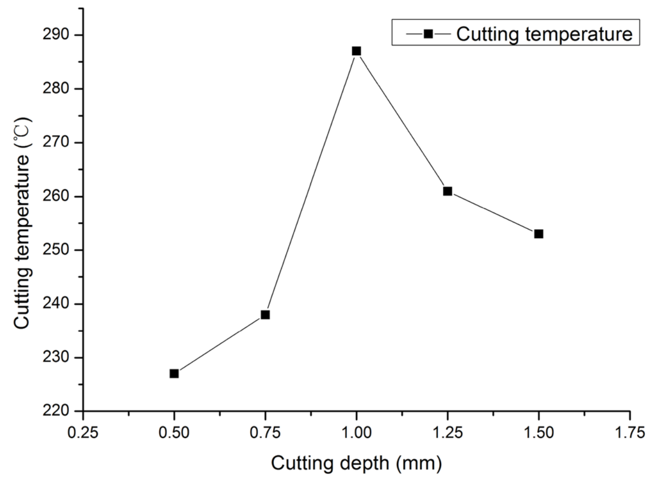


Fig. 11 Evolution of cutting temperature against cutting time at different depth of cut with PCD tools (cutting speed 60 m/min, feed rate 0.1 mm/r)

3.3.2 Influence of feed rate

Figure 10 shows the evolution of cutting temperature against feed rate with PCD tools. With the increase of feed rate, the squeeze and the rubbing between tool and workpiece become more and more seriously. The nose of tool withstands more cutting force and the insert fractures at higher feed rate. On the other hand, the increasing of the chip thickness takes more heat away and changes the friction condition and heat distribution at the cutting zone [32]. So, cutting temperature increases firstly and drops then. However, it is reported that cutting temperature increases with increase of feed rate in turning TC4 with coated cemented carbide due to severe chipping, plastic deformation of the tools and so on [5]. The cutting temperature in present study is much lower than An's study [34] due to different material of cutting tool.

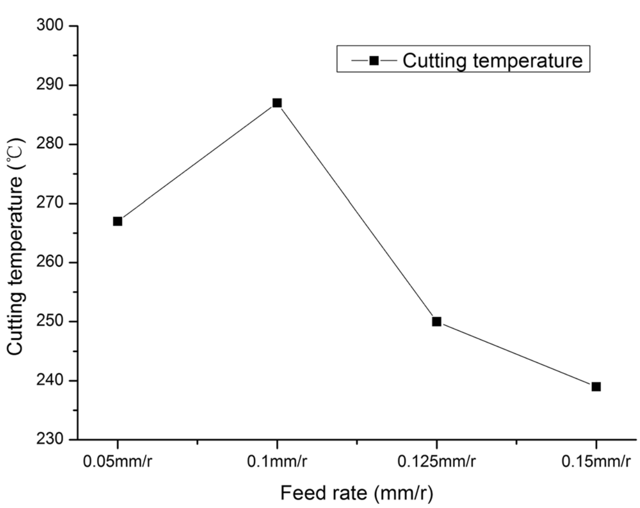


Fig. 10 Evolution of cutting temperature against cutting time at different feed rate with PCD tools (cutting speed 60 m/min, depth of cut 1.0 mm)

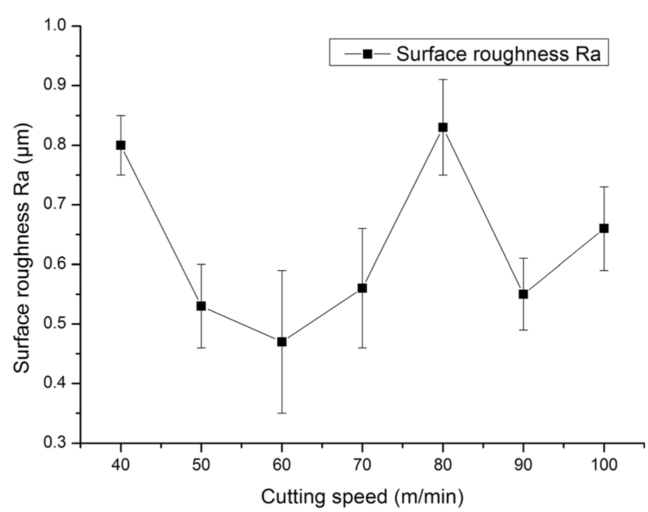


Fig. 12 Evolution of surface roughness against cutting speed with PCD tools (feed rate 0.10 mm/r, depth of cut 1.0 mm)

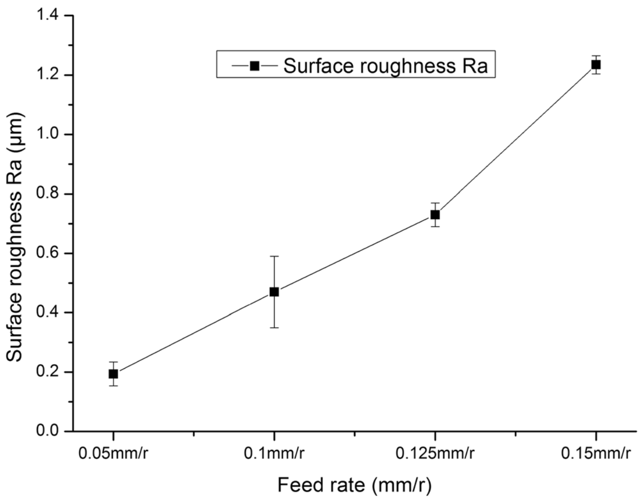


Fig. 13 Evolution of surface roughness against feed rate with PCD tools (cutting speed 60 m/min, depth of cut 1.0 mm)

3.3.3 Influence of the depth of cut

Figure 11 shows the evolution of cutting temperature against depth of cut with PCD tools. With the increase of depth of cut, more material of workpiece adhered onto cutting tool. The heat and force generated during the cutting process are higher at larger depth of cut [14]. So, cutting temperature rises before depth of cut reaches 1.0 mm. After that, cutting heat dissipates more smoothly and cutting temperature goes down gradually.

3.4 Influence of cutting parameters on surface roughness using PCD tools

3.4.1 Influence of cutting speed

Figure 12 shows evolution of surface roughness against cutting speed with PCD tools. The surface roughness fluctuates between Ra 0.45 and Ra 0.80 μm with the increase of cutting speed from 40 to 100 m/min. Generally, surface roughness decreases with the increase of cutting speed [3]. At higher cutting speed of 60 m/min, the surface roughness reaches the lowest value. The more cutting heat is produced, the adhered materials of workpiece drop from the tool or high cutting temperature softens the surface of workpiece, which may

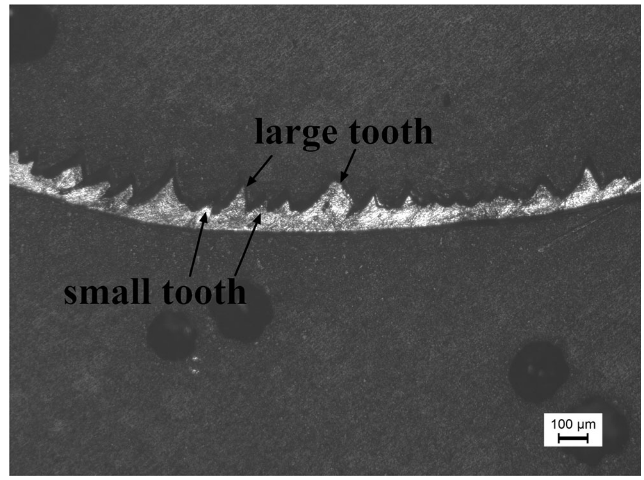


Fig. 15 Cross section of chip at feed rate of 0.10 mm/r

cause the surface roughness to fall at cutting speed of 60 m/min [11]. If measures are taken to decrease the cutting temperature, surface roughness will keep small and stable [35]. For cutting speed of 80 m/min, high cutting speed results in severe wear and high cutting force, so surface roughness increases. The decrease of surface roughness with increase of cutting speed is reported in turning of TC4. But the surface roughness does not increase at higher cutting speed due to high-pressure coolant applied and the properties of cutting tool, which is different to the result of present study [18].

3.4.2 Influence of feed rate

Figure 13 shows evolution of surface roughness against feed rate with PCD tools. When feed rate increases, cutting temperature and cutting force rise, which leads to serious tool wear. Tool wear is a significant factor for surface roughness of material [36]. The built-up layer can push the tool off from its original route; the adhered materials of workpiece tear off and cutting force changes correspondingly. The serious tool wear can lead to micro-pits and debris on the machined surface [37]. So, surface roughness increases with the increase of feed rate, which is also investigated during machining TC6 under dry condition [24]. But surface roughness is much lower at feed rate of 0.13 mm/r than that in present study because the manufacturing processing and tool material are different.


(a) (b) (c)

Fig. 14 Chip formation **a** feed rate at 0.10 mm/r; **b** feed rate at 0.125 mm/r; **c** feed rate at 0.15 mm/r

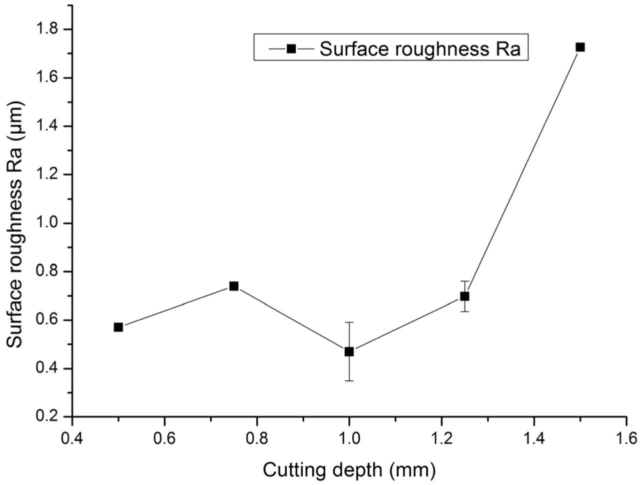


Fig. 16 Evolution of surface roughness against depth of cut with PCD tools (cutting speed 60 m/min, feed rate 0.10 mm/r)

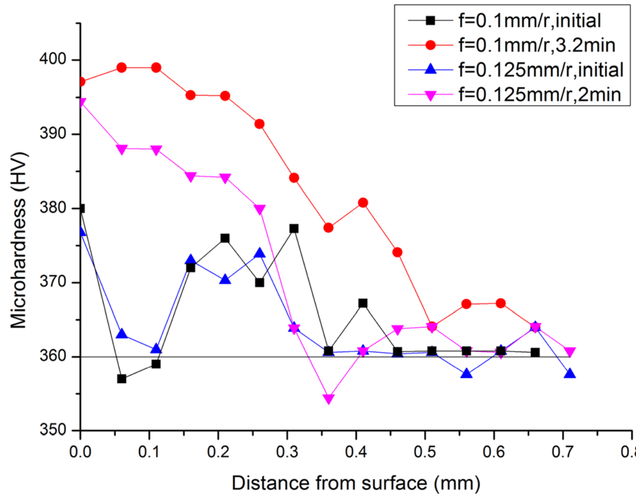


Fig. 18 Evolution of surface microhardness profile beneath surface of machined workpiece at different feed rate with PCD tools (cutting speed 60 m/min, depth of cut 1.0 mm)

The chip formation also deteriorates with increase of feed rate. Figure 14 shows chip formation at different feed rate. It can be seen that chip becomes long and continuous with increase of feed rate. It is reported that continuous chip is produced by the shearing of the workpiece material along the primary shear zone [31]. Continuous chip is undesirable in machining because it can twist on the workpiece or tool and damage the machined surface [23, 34].

Figure 15 shows the cross section of chip at feed rate of 0.10 mm/r. It can be seen that serrated chip occurs during machining. It is reported that serrated teeth size and their number per given length indicate presence or absence of chatter during machining [3]. The chip contains large tooth and relatively small tooth, which is an indication of chatter. The chatter can cause the fluctuation of cutting force, deteriorate the machined surface, and speed up the wear of cutting tool, and so on [38].

3.4.3 Influence of the depth of cut

Figure 16 shows evolution of surface roughness against depth of cut with PCD tools. With the increase of depth of cut, the cutting force, cutting temperature, and the wear of cutting tool increase. On the other hand, the contact between cutting tool and workpiece increases, which is helpful for dissipation of the cutting heat and the softening of workpiece surface layer. All these factors cause the surface roughness to keep stable at relatively low depth of cut. When depth of cut is too large (1.5 mm), the surface roughness increases sharply, which can be attributed to the severe wear of cutting tool or the formation of built-up layer on the cutting tool [39]. In cutting parameters, the depth of cut shows minimal effect on surface roughness [40].

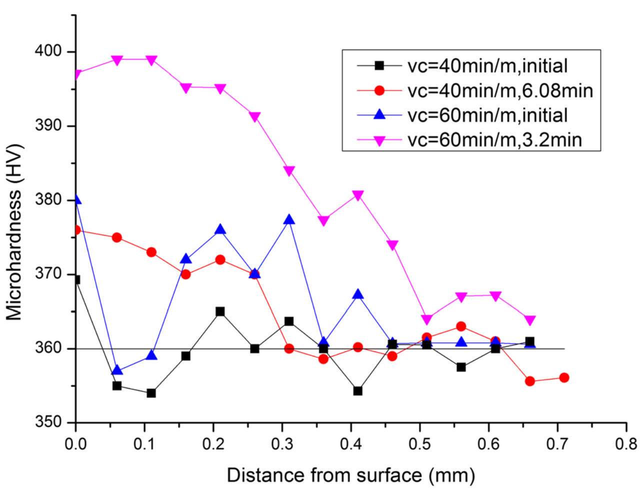


Fig. 17 Evolution of surface microhardness profile beneath surface of machined workpiece at different cutting speed with PCD tools (feed rate 0.10 mm/r, depth of cut 1.0 mm)

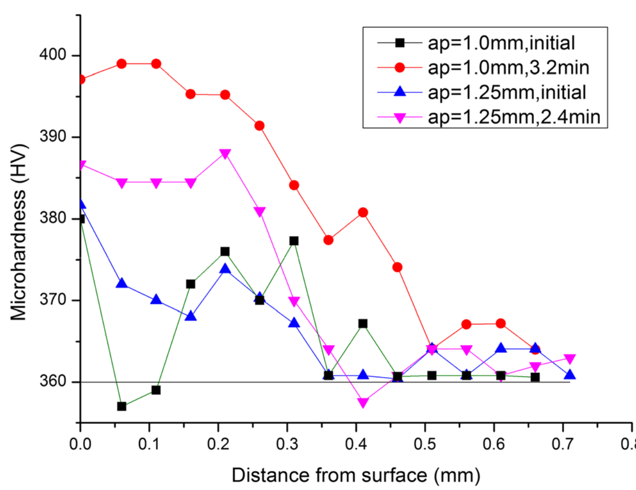


Fig. 19 Evolution of surface microhardness profile beneath surface at different depth of cut with PCD tools (cutting speed 60 m/min, feed rate 0.10 mm/r)

3.5 Influence of cutting parameters on surface microhardness using PCD tools

3.5.1 Influence of cutting speed

Figure 17 shows evolution of surface microhardness profile beneath surface of machined workpiece with PCD tools at two cutting speeds. After machining, the microhardness reaches the peak value near the surface and then drops gradually to hardness of bulk material. It is evident that hardness at cutting speed of 60 m/min is higher than that at the cutting speed of 40 m/min. Schoop, et al. [16] pointed out that high cutting force caused by high cutting speed resulted in stronger strain hardening than thermal softening caused by high cutting temperature. The higher cutting force helps to produce deeper hardening layer at higher cutting speed of 60 m/min.

The microhardness of subsurface at 0.05–0.1 mm beneath the machined surface is lower than the average hardness of the bulk material. At this depth, the effect of softening is much greater than that of work hardening during plastic deformation or microstructure alteration of the subsurface. The softening effect caused by high cutting temperature is characterized by the effect of aging process. During the aging, microhardness decreases [41, 42]. The microhardness at the middle cutting stage is higher than the average hardness. It is found that the wear of cutting edge affects the microstructure of surface layer of workpiece and increases the cutting force. So greater surface hardening takes place when machining with worn tools of PCD [8]. The surface hardening was observed in high-speed milling of TA15 and end milling of TC4. However, the depth of surface hardening layer is lower than that of present study probably due to poorer machinability of TC7, the different machining processing and so on [1, 42].

3.5.2 Influence of feed rate

Figure 18 shows evolution of surface microhardness profile beneath surface of machined workpiece with PCD tools at two feed rates. At initial cutting stage, the microhardness profile at two feed rates is similar to that at two cutting speeds. However, the hardness decreases when the feed rate increases from 0.1 to 0.125 mm/r. The effect of thermal softening induced by high cutting temperature causes the decrease of hardness at higher feed rate of 0.125 mm/r. When feed rate goes up, cutting force increases, which leads to more cutting heat and softens the machined surface layer. The adhered workpiece material on the tool drops at high cutting temperature. The tool becomes relative sharper and the wear rate slows down, so the hardness of surface layer and depth of hardening surface layer are lower at feed rate of 0.125 mm/r [1].

In present study, the maximum microhardness is 400 HV. It is lower than the maximum microhardness 420 HV in turning Ti6246 [36, 43]. The reason can be the higher hardness of bulk material, the serious worn cutting tool when turning Ti6246 with uncoated carbide tools [43].

3.5.3 Influence of the depth of cut

Figure 19 shows evolution of surface microhardness profile beneath surface of machined workpiece with PCD tools at two depth of cut. At higher depth of cut of 1.25 mm, the microhardness is lower than that of 1.0 mm. With the increase of depth of cut, more cutting heat occurs, which softens the surface layer. The depth of cut has a little influence on wear rate of cutting tools. All these factors result in the low microhardness at depth of cut at 1.25 mm.

4 Conclusion

1. Non-uniform wear band forms on the both tools of PCD and PCBN. During the machining, the strong chemical reactivity, affinity, and diffusivity of TC7 alloy result in the thick adhered materials of workpiece on both tool surface. The main wear mechanism of PCD tools are adhesion, chipping, and adhesion-dissolution-diffusion. The main wear mechanism of PCBN tools is adhesion, notching, crater, and adhesion-dissolution-diffusion.
2. PCD tools have better performance of wear resistance, compared with PCBN tools. The life of PCD tools is longer than that of PCBN tools. The cutting parameters suitable for PCD tools are higher than that suitable for PCBN tools. PCD tools are more suitable for machining the titanium alloy. Within reasonable range of cutting parameters, the life of PCD tools is relatively longer. By making comparisons of PCD performance during machining TC7 and TC4, it can be made a conclusion that machinability of TC7 is poorer than that of TC4.
3. When machining with PCD tools, the cutting temperature increases with the increase of cutting speed. High cutting temperature softens the surface layer of workpiece, which makes the surface roughness decrease. The increase of feed rate causes serious squeeze and rubbing between tools and workpiece, so cutting temperature increases and the surface roughness increases. The cutting temperature reaches peak value at depth of cut at 1.00 mm, while the surface roughness keeps stable relatively when depth of cut increases.
4. The hardening of workpiece surface layer occurs during machining with PCD tools. The microhardness becomes higher with the increase of cutting speed, which results from the stronger strain hardening than softening effect and the wear of cutting tool at high cutting speed. Because the high cutting temperature softens the surface layer of workpiece, the microhardness of surface layer decreases with the increase of feed rate and depth of cut,

respectively. At initial stage of cutting, the effect of softening also occurs because of the same reason.

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