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ORIGINAL ARTICLE

Effects of cutting parameters on dry machining Ti-6Al-4V alloy with ultra-hard tools

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Abstract Polycrystalline cubic boron nitride (PCBN) and polycrystalline diamond (PCD) cutting tools were used in dry machining Ti-6Al-4V titanium alloy. Their main failure mechanisms were analyzed with a scanning electron microscope (SEM) and an energy-dispersive spectrometer (EDS). Effects of cutting parameters (cutting speed and feed rate) on tool life, cutting temperature, workpiece surface roughness, and surface microhardness were characterized with a 3-D super-depth-of-field instrument, a handheld infrared thermal imager, a surface profile measuring instrument, and a microhardness tester, respectively. The results showed that the main failure mechanisms of the PCBN tool were chipping, notch, adhesion, and crater. And, the main failure mechanisms of the PCD tool were adhesion, crater, and dissolution-diffusion. The strong diffusivity of PCD material made the performance of the PCD tool better than that of the PCBN tool. When cutting speed increased in machining with the PCD tool, decreasing cutting temperature caused by the reduction of adhered workpiece material on the tool surface resulted in a lower tool wear rate at the cutting speed of 80 m/min, and workpiece surface roughness initially increased and then decreased. The surface roughness initially increased, and after the feed rate of 0.10 mm/r, the surface roughness basically kept a constant value with feed rate increasing. High cutting speed and high feed rate increased and decreased the hardening rate of machined workpiece surface layer in machining with PCD tool, respectively.

Keywords PCBN tool · PCD tool · Ti-6Al-4V titanium alloy · Main failure mechanisms · Cutting parameters

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1 Introduction

Titanium and titanium alloys are extraordinarily attractive for machinery and medical industry [1]. They possess biological compatibility, high strength to density ratio, and excellent corrosion resistance relative to other metal materials. However, their mechanical and chemical properties bring poor machinability [2]. During their cutting process, their small deformation coefficient causes a small contact area of tool-chip interface, resulting in high cutting pressure on cutting edge of cutting tool. It gives rise to the formations of fracture and plastic deformation on the cutting edge. Adhesion of workpiece material on cutting tool is caused by high affinity of titanium and titanium alloys. The adhered workpiece material is easily tore and stripped to develop crater on cutting tool surface. Low thermal conductivity of titanium alloys induces very high cutting temperature to accelerate wear rate of cutting tool [2].

Polycrystalline cubic boron nitride (PCBN) and polycrystalline diamond (PCD) are ultra-hard materials. They have extraordinarily high hardness, high thermal conductivity, and excellent thermal stability [2–4]. Due to the superior performances, the two cutting tools have been seen as optional tools to machine titanium and titanium alloys. Compared with the machining performance of cemented carbide tool, the PCBN tool and the PCD tool are more suitable to high-speed machine titanium alloys [3, 4], and the machined workpiece surface roughness is better when machining with the two cutting tools [5], although the PCBN tool gives a lower performance in terms of tool life [6].

The main wear mechanisms of PCBN and PCD cutting tools are closely related to cutting temperature in machining titanium alloys [2, 7]. Zoya and Krishnamurthy [8] indicated that the high cutting temperature of around 700 °C was very critical temperature to constrain the performance of PCBN tools in machining titanium alloys. Some researchers have used high-pressure coolant supplies to improve the cutting tool performance when cutting titanium alloys in order to reduce cutting temperature [5, 9]. The high coolant supplies can improve the tool performance at a high cutting speed [9].

In the most previous lines of research, PCBN and PCD tools were only used in the milling process of titanium alloys. Little attention is paid to the machining performances of ultra-hard cutting tools with dry turning titanium alloys, especially the effects of cutting parameters on cutting temperature. In this paper, dry machining experiments of Ti-6Al-4V alloy with PCBN and PCD tools were carried out to study the machining performance of the two cutting tools. Their tool wear mechanisms were studied and compared, and the effects of cutting speed and feed rate, on tool life, cutting temperature, and workpiece surface integrity were investigated.

2 Experimental material and program

2.1 Experimental material

Ti-6Al-4V rods with a diameter of 100 mm and a length of 500 mm were used as machined material. The chemical composition and the mechanical properties are shown in Tables 1 and 2, respectively. PCBN and PCD tools with designation CNGA120404 were used. Cemented tungsten carbide (wt. 8 % of Co) was utilized as their tool body material. The PCBN and PCD inserts were embedded in the tool body. Furthermore, the PCBN material contained 90 wt% cubic boron nitride (CBN) with 10 wt% Al+Ni+Co as a metallic-type binder. A MCKNR2020K12 tool holder was used. The combination of the tool holder and the two inserts provided the tool angle parameters as shown in Table 3.

2.2 Experimental program

The cutting experiments were carried out on a CNC CKA6150i lathe without lubricant and coolant. A SEM and an EDS were used to characterize wear morphologies and surface chemical composition of worn tool, respectively. An acid solution (4 % HF+6 % HNO_3+90 % H_2O) was used to remove the adhered workpiece material on the tool surfaces. The tool surface morphologies after etching were characterized by SEM. Average flank wear (VB) of the worn tool, cutting temperature, surface roughness of machined workpiece, and microhardness of the machined workpiece surface layer were measured with a VHX-600E 3-D super-depth-of-field instrument, a RC10+ handheld infrared thermal imager, a BMT Expert 3-D surface profile measuring instrument, and a MVS 1000D1 microhardness tester, respectively. The effects of cutting speed and feed rate on the tool life, cutting temperature, surface roughness, and surface microhardness were analyzed.

Table 1 Chemical composition of Ti-6Al-4V alloy (wt%)

Ti	Al	V	Sn	Fe	Si	Mo
89.70	6.31	3.28	0.43	0.24	0.04	0.01

Table 2 Mechanical properties of Ti-6Al-4V alloy

Tensile strength (σ_b/MPa)	Yield strength ($\sigma_{0.2}$/MPa)	Elongation (δ/%)	Vickers hardness (HV)
901.87	853.33	7.52	347.40

3 Results and discussion

3.1 Wear mechanisms of PCBN and PCD tools

3.1.1 Flank face wear

Figures 1 and 2 show the SEM photographs of worn flank faces of PCBN and PCD tools, respectively. Nonuniform flank wear bands are observed to appear on the two cutting tools. The workpiece materials are adhered on the flank faces. Titanium has strong chemical reactivity with almost all cutting tool materials at the high cutting temperature [9]. The very low thermal conductivity of the titanium alloy causes high cutting temperature during the cutting process. The combination of high chemical reactivity and contact pressure of tool-workpiece interface helps the formation of the adhered workpiece material. The adhered workpiece material can be stripped by the workpiece surface, and adhesive force results in plucking out of the cutting tool material [10]. As shown in Fig. 2c, slight stripping appears on the PCD tool.

Figure 1b shows the SEM photograph of notch on the PCBN tool. The plucking process tends to remove any loose PCBN tool material from the cutting edge, inducing the formation of the notch [4]. Chipping is also observed in Fig. 1a, c. Serrated chip formation, as an inherent characteristic of machining titanium and titanium alloys, leads to highly periodic fluctuation of cutting force [9]. It causes the formation of the chipping wear.

Table 4 shows the chemical composition analysis of areas selected in Figs. 1b and 2b. The chemical composition

Table 3 Angle parameters of PCBN tool and PCD tool

	Rake angle	Relief angle	Cutting edge angle	Minor edge angle
PCBN	6°	0°	95°	5°
PCD	4°	0°	95°	5°

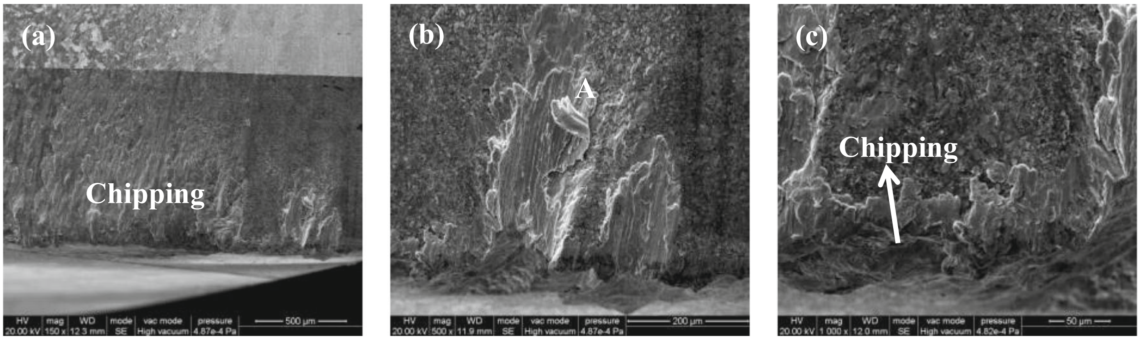


Fig. 1 SEM photographs of worn flank face of PCBN tool after 4-min machining: **a** flank face, **b** notch, and **c** cutting edge (cutting speed of 40 m/min, feed rate of 0.1 mm/r, and cutting depth of 1.0 mm)

analysis of area A demonstrates that although the binder cobalt exists, there are no the main elements of the PCBN tool, nitrogen, and boron. And, the chemical composition of area B contains approximately 51 wt% carbon and 42 wt% titanium. Obviously, the diffusion of carbon element across the adhered workpiece material results in the formation of titanium carbide layer at tool/workpiece interface in machining with the PCD tool [11], while there is not the formation of corresponding titanium compounds due to the inexistences of nitrogen and boron elements on the worn PCBN tool surface.

To further study wear mechanisms of the PCD tool flank face, the adhered workpiece material was etched by an acid solution (4 % HF+6 % HNO_3+90 % H_2O). Figure 3 shows the SEM photographs of flank face of PCD tool after etching. Notch appears on the flank face at some distance from the tool nose. Intimate contact of tool-workpiece interface and high chemical reactivity at high cutting temperature generate adhesion-dissolution-diffusion [9]. As shown in Fig. 3b, very rough surface is caused by plucking and stripping of the adhered workpiece material. The PCD particles are plucked during the stripping process. Besides, the rough surface supplies an ideal environment for adhesion-dissolution-diffusion [11].

3.1.2 Rake face wear

Figures 4 and 5 show the SEM photographs of rake faces of PCBN and PCD tools, respectively. Adhesion is observed to form on the rake faces of the two cutting tools. More severe crater forms on the PCBN tool, compared with crater morphology on the PCD tool. It can be concluded that the resistance of the PCD tool to crater is better than that of the PCBN tool. When chip flows across rake face of cutting tool, high affinity of the titanium alloy and intimate contact of tool-chip interface give rise to the formation of the adhered workpiece material layer. The adhered workpiece material layer serves as a protective layer from further tool wear. However, during the machining process, the adhered workpiece material layer can be torn and stripped by the underside of chips. Cutting tool particle material is carried off leaving the formation of crater. Therefore, the combination of the protective action and the stability of the protective layer determines the resistance to crater wear [4]. For the PCBN cutting tool, the tool material is decomposed into nitride and boron; there are the formations of titanium nitride and titanium boron. While the cutting process is carried out with the PCD tool, a titanium carbide layer forms [12]. From the above analysis, the titanium carbide layer appears on the tool/workpiece interface in machining with the PCD tool, while there is not the corresponding titanium

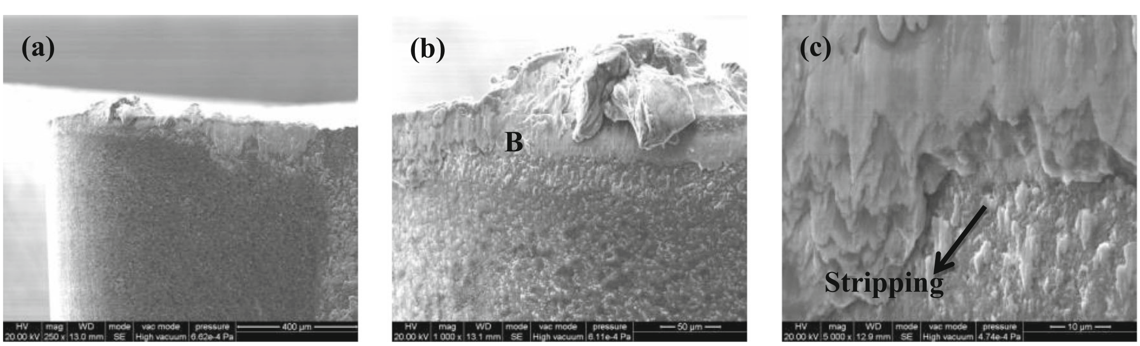
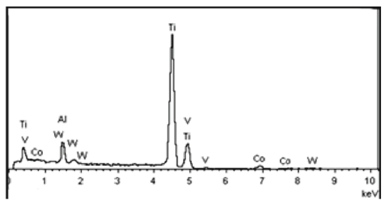
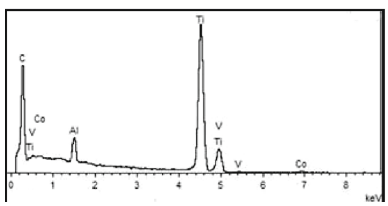


Fig. 2 SEM photographs of worn flank face of PCD tool after 6-min machining: **a** flank face, **b** adhered workpiece material, and **c** stripping (cutting speed of 60 m/min, feed rate of 0.1 mm/r, and cutting depth of 1.0 mm)

Table 4 Chemical composition of areas selected in Figs. 1b and 2b

Area	EDS spectrum	Chemical composition (wt%)
A		Al, 7.27 Ti, 81.05 V, 3.69 Co, 4.32 W, 3.67
B		C, 51.04 Al, 3.37 Ti, 42.45 V, 2.29 Co,0.84

compound layer with the PCBN tool. It can be caused by stronger diffusivity of PCD material than that of PCBN material. The strong diffusivity of the PCD tool material generates the stronger bonding strength between the tool surface and the adhered workpiece material layer, and the formation of the titanium carbide protective layer is also caused by the strong diffusivity on the PCD tool surface. The performance of PCD tool is prone to be better than that of PCBN tool, which may be attributed to the strong diffusivity of PCD material with the titanium alloy.

As shown from Fig. 4c, chipping forms at cutting depth from tool nose on the PCBN tool. Work hardening layer exists on workpiece surface layer. A high rate of work hardening is one factor for their poor machinability during machining titanium and its alloys [10]. The work hardening layer contributes to the formation of the chipping. With respect to the morphologies of the PCD tool, there is no the emergence of chipping. It shows that the resistance of PCD tool to chipping is much better than that of PCBN tool.

3.2 PCBN and PCD tool life analysis

3.2.1 Influence of cutting speed

Figure 6a, b shows the progressions of average flank wear VB versus cutting time at different cutting speeds in machining with the PCBN and the PCD tools, respectively. When machining with the both cutting tools, the tool wear rate is initially highest and then levels off as the cutting time further increasing. Wang et al. [13] also observed that flank wear rate kept steady after a rapid initial wear when they used binderless CBN tools to high-speed mill titanium alloys. From the above analysis on the wear mechanisms of the two cutting tools, their main failure mechanisms are related to the cutting temperature. Wanigarathne et al. [14] found that the rates of tool wear and cutting temperature were high at the initial machining process. They came to the conclusion that the high initial tool wear rate coincided with the high temperature rate. It can be seen that the high wear rate at the beginning of machining is attributed to the high cutting temperature.

As shown from Fig. 6a, with the increase of cutting speed, increasing cutting force and increasing cutting temperature speed up the tool wear rate in machining with the PCBN tool. In Fig. 6b, when the workpiece is machined by the PCD tool, the tool wear rate increases with cutting speed increasing from 40 to 60 m/min. However, the average flank wear at the cutting speed of 80 m/min is lower, compared with that at the cutting speeds of 60 and 100 m/min. With the increase of cutting speed, the increasing cutting temperature weakens the formation condition of the adhered workpiece material layer, decreasing the friction between the chip and the tool surface. The cutting temperature can appear to be a slight reduction in a high cutting speed period, resulting in the lower average flank wear at the cutting speed of 80 m/min. However, when the cutting speed is beyond the cutting speed period, the cutting temperature continues to increase with cutting speed increasing. Hence, when cutting speed is

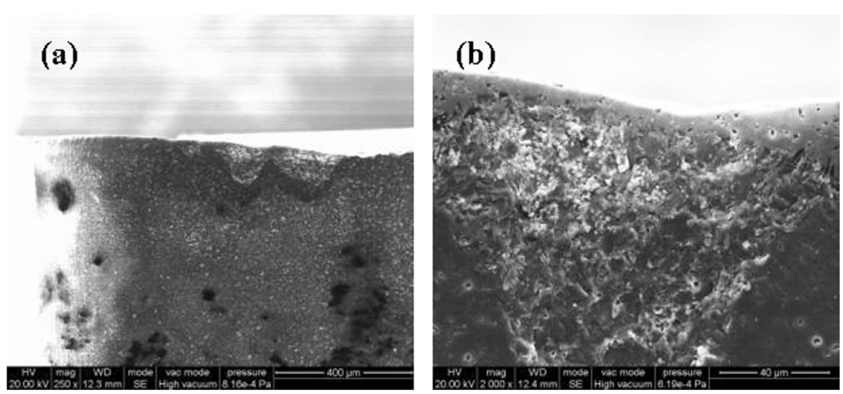


Fig. 3 SEM photographs of flank face of PCD tool etched after 6-min machining: **a** flank face and **b** notch (cutting speed of 60 m/min, feed rate of 0.1 mm/r, and cutting depth of 1.0 mm)

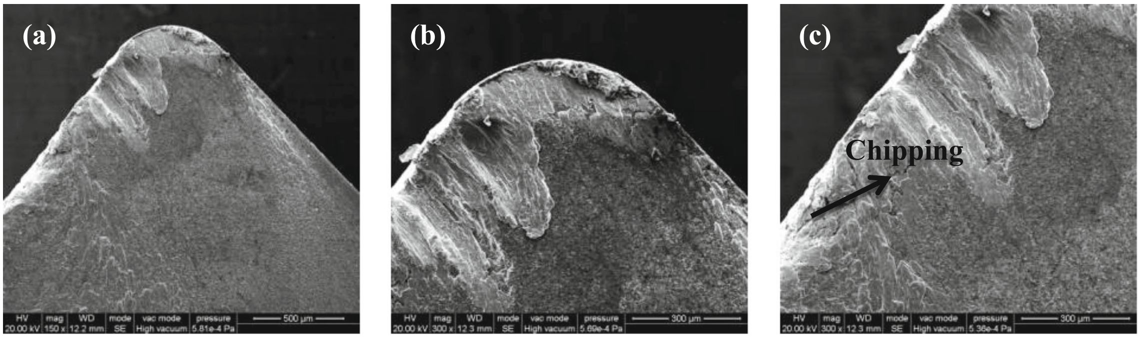


Fig. 4 SEM of rake face of PCBN tool after 4-min machining: **a** rake face, **b** tool nose, and **c** at cutting depth from tool nose (cutting speed of 40 m/min, feed rate of 0.1 mm/r, and cutting depth 1.0 mm)

beyond 80 m/min, average flank wear increases with the increase of cutting speed. Furthermore, the cutting temperature reduces the joint strength of the welding region between the PCD insert and the tool body. At the cutting speed of more than 60 m/min, the PCD insert drops from the tool body after machining for approximately 10 min.

3.2.2 Influence of feed rate

Figure 7a, b shows the progressions of VB versus cutting time at different feed rates in machining with the PCBN and PCD cutting tools, respectively. With the increase of feed rate, the VB of the both cutting tools increases. The increasing feed rate increases the cutting amount per unit time. Consequently, the cutting temperature increases with feed rate increasing. Based on the previous analysis, the wear rate of the cutting tool is closely related to the cutting temperature. The high cutting temperature results in faster diffusion kinetics and aggravates the extents of adhesion wear and crater wear, resulting in the increase of the tool wear rate [15].

From the influences of cutting speed and feed rate on the service life of the both cutting tools, the life of the PCBN tool is much shorter than that of the PCD tool under the same cutting conditions. It can be concluded that the PCD tool is more suitable to machine the titanium alloy compared with the PCBN tool. In the following analysis, the cutting temperature and the machined workpiece surface integrity by the PCBN tool are not discussed.

3.3 Influence of cutting parameters on cutting temperature with PCD tool

The low thermal conductivity of the titanium alloy makes the cutting temperature very high. Especially in such a case that the chemical reactivity of the workpiece material with almost all cutting tool materials has a close relationship with the cutting temperature, the cutting temperature is a key factor to affect the machining performance of cutting tool.

3.3.1 Influence of cutting speed

Figure 8 shows the progression of cutting temperature versus cutting speed in machining with PCD tool. Although the increasing cutting speed makes the chip bring more heat away, the cutting temperature increases with cutting speed increasing except 80 m/min. The amount of the adhered workpiece material on the tool surface decreases under the influence of high cutting temperature at a high cutting speed, weakening the friction between the chip and the tool surface. The cutting

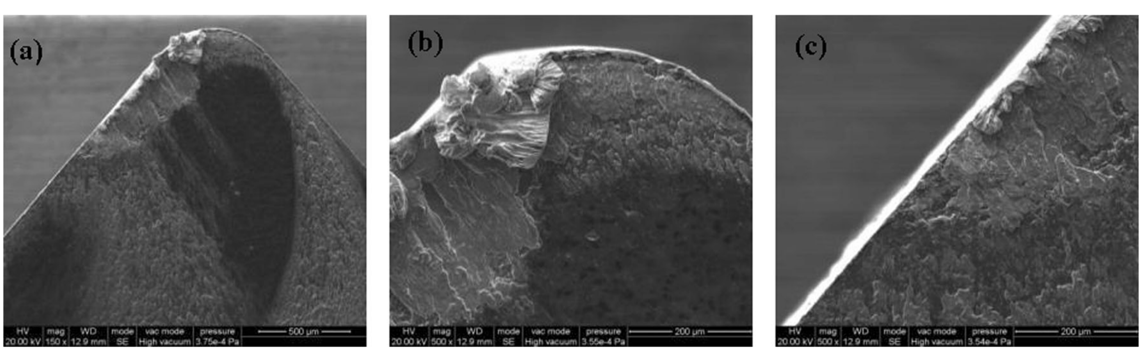


Fig. 5 SEM photographs of rake face of PCD tool after 6-min machining: **a** rake face, **b** tool nose, and **c** at cutting depth from tool nose (cutting speed of 60 m/min, feed rate of 0.1 mm/r, and cutting depth of 1.0 mm)

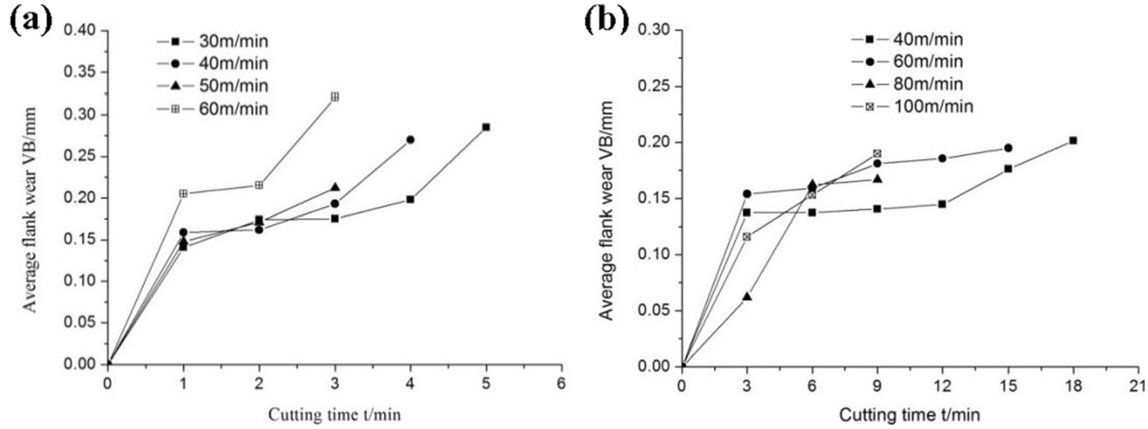


Fig. 6 Progression of VB versus cutting time at different cutting speeds in machining with **a** PCBN tool and **b** PCD tool (feed rate of 0.10 mm/r and cutting depth of 1.0 mm)

temperature appears to be a lower value at the cutting speed 80 m/min. With cutting speed increasing beyond 80 m/min, the influence of increasing cutting speed on the adhered workpiece material layer is weakened, and the cutting temperature continues to increase. The phenomenon confirms the explanation for the improvement of the PCD tool at the cutting speed of 80 m/min.

3.3.2 Influence of feed rate

Figure 9 shows the progression of cutting temperature versus feed rate in machining with PCD tool. With the increase of feed rate, the cutting amount per unit time increases, resulting in the increase of plastic deformation. And, when the feed rate is raised, the thickness of the chip produced during the cutting process increases, changing the friction condition between the chip and the tool rake face. Both of the reasons can result in the increase of cutting temperature with feed rate increasing.

3.4 Influence of cutting parameters on surface roughness with PCD tool

3.4.1 Influence of cutting speed

Figure 10 shows the progression of surface roughness versus cutting speed. With the increase of cutting speed, the surface roughness initially increases and then decreases at the cutting speed of more than 60 m/min. At the cutting speed of 60 m/min, the surface roughness reaches the peak value. When the cutting speed is from 15 to 60 m/min, the increase of cutting speed raises the cutting force and the cutting temperature. The elevated cutting force and cutting temperature lead to high tool wear rate. The explanation for increasing in surface roughness is the high tool wear at the cutting speed ranging from 15 to 60 m/min. At the high cutting speed of more than 60 m/min, due to the high cutting temperature, the amount of the adhered workpiece material decreases, weakening the friction between the chip and the

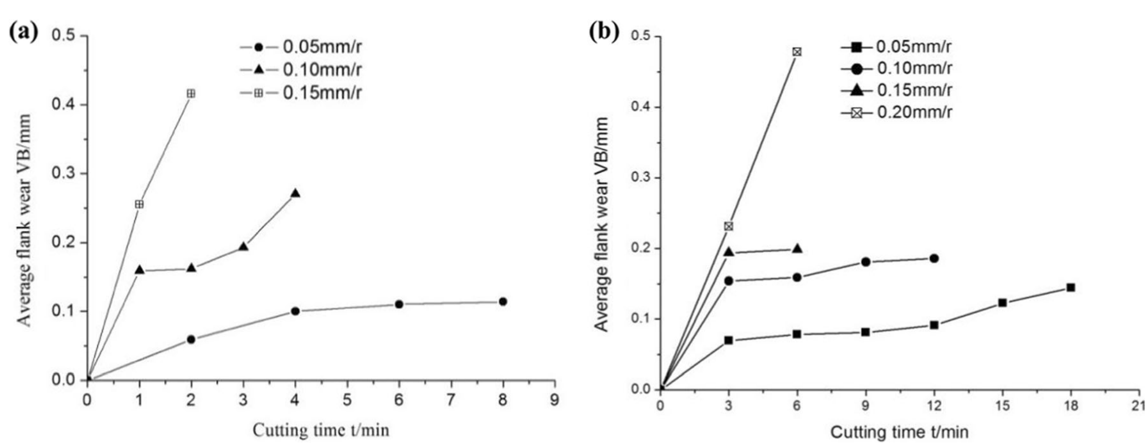


Fig. 7 Progression of VB versus cutting time at different feed rates in machining with **a** PCBN tool (cutting speed of 40 m/min and cutting depth of 1.0 mm) and **b** PCD tool (cutting speed of 60 m/min and cutting depth of 1.0 mm)

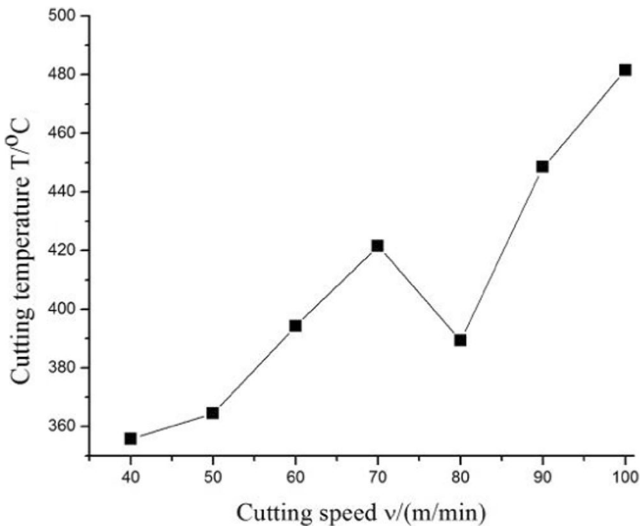


Fig. 8 Progression of cutting temperature versus cutting speed in machining with PCD tool (feed rate of 0.10 mm/r and cutting depth of 1.0 mm)

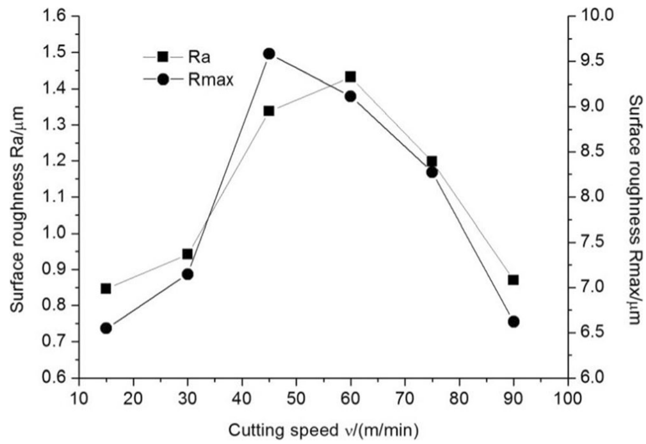


Fig. 10 Progression of surface roughness versus cutting speed in machining with PCD tool (feed rate of 0.10 mm/r and cutting depth of 1.0 mm)

tool surface [16]. And, the thermal softening reduces the workpiece strength [17]. Both of the aspects result in the decreases of cutting force. The decreasing cutting force brings small tool vibration to improve surface roughness.

3.4.2 Influence of feed rate

Figure 11 shows the progression of surface roughness versus feed rate. The very low feed rate of 0.05 mm/r makes the tool nose curvature not participate fully in cutting, leading to the result that surface roughness initially decreases with feed rate increasing from 0.05 to 0.065 mm/r. When the feed rate is beyond 0.065 mm/r, the high tool wear is caused by high cutting temperature and high cutting force with feed rate increasing. The tool wear has a strong impact on the surface roughness of the machined workpiece [18]. The high tool wear results in tearing of the workpiece surface and debris deposited on the machined surface, increasing the surface roughness value [19]. The surface roughness increases with feed rate increasing.

The surface roughness basically keeps a constant value at the feed rate of more than 0.10 mm/r. At a high feed rate, the elevated cutting temperature softens the workpiece surface, decreasing the cutting force to improve the debris defect. And, the elevated cutting temperature reduces the amount of the adhered workpiece material on the tool surface, lightening the tearing defect on the machined workpiece surface. The photographs of machined workpiece surface by the PCD tool at different feed rates are shown in Fig. 12. The tearing and the debris at the feed rate of 0.21 mm/r are much slighter than those at the feed rate of 0.10 mm/r, although the feed mark defect becomes worse at the high feed rate. Accordingly, the

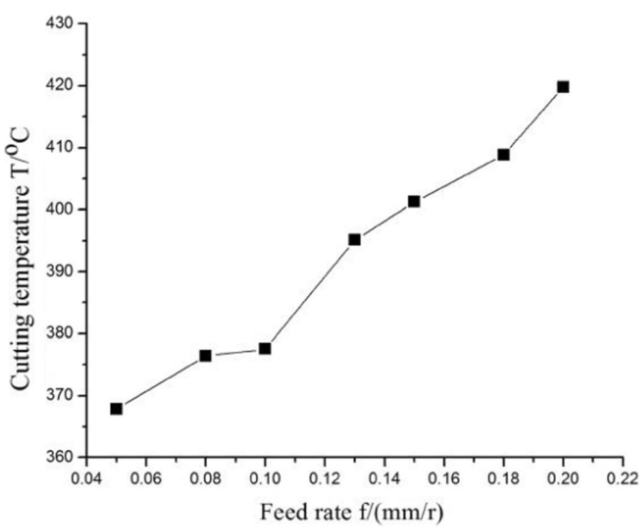


Fig. 9 Progression of cutting temperature versus feed rate in machining with PCD tool (cutting speed of 50 m/min and cutting depth of 1.0 mm)

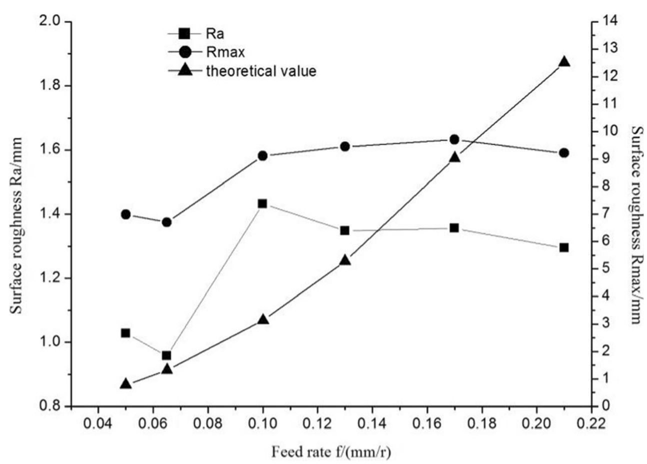


Fig. 11 Progression of surface roughness versus feed rate in machining with PCD tool (cutting speed of 60 m/min and cutting depth of 1.0 mm)

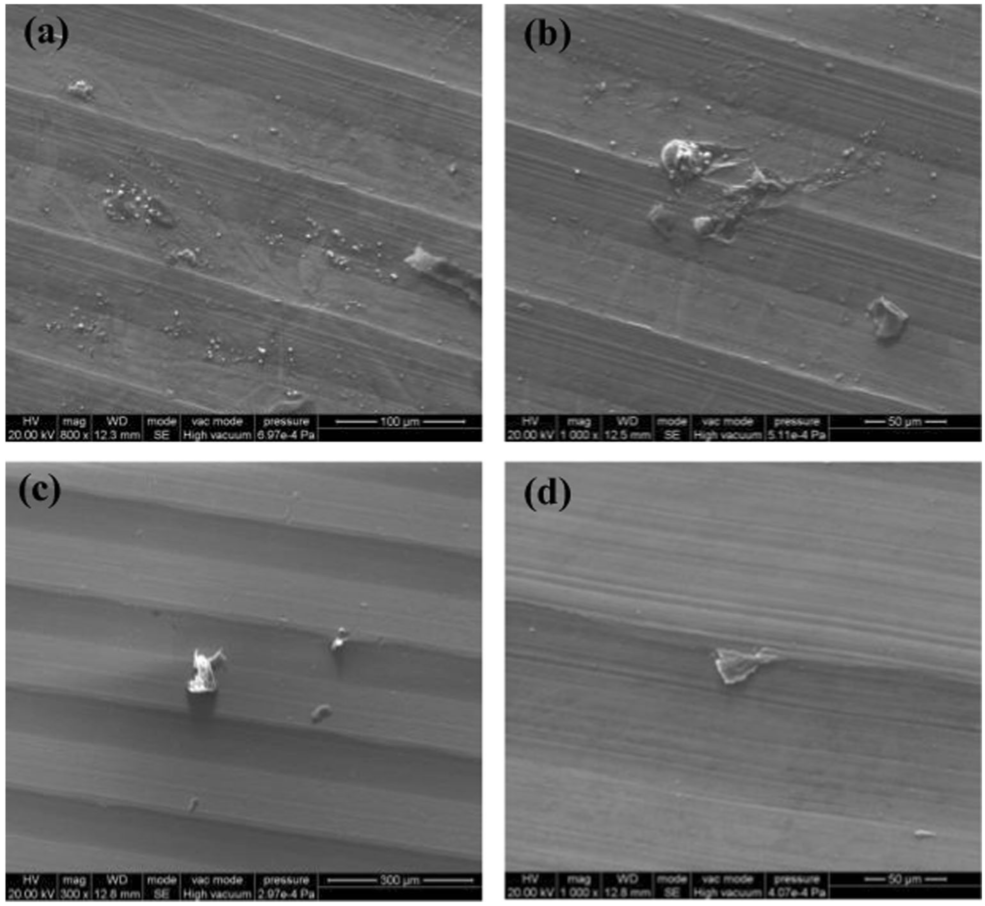


Fig. 12 SEM photographs of machined workpiece surface by PCD tool at different feed rates: **a** debris and **b** tearing at the feed rate of 0.10 mm/r and **c** debris and **d** tearing at the feed rate of 0.21 mm/r (cutting speed of 60 m/min, feed rate of 0.1 mm/r, and cutting depth of 1.0 mm)

thermal softening and the reduction of the adhered workpiece material cause the results that surface roughness basically levels off at the feed rate of more than 0.10 mm/r with feed rate increasing.

When a cutting process is carried out by a cutting tool with a circular blade, a basic theoretical model for workpiece surface roughness R_{max} is approximated by the following equation [20]:

$$R_{\max} = \frac{f^2}{8r_{\in}}$$

where f denotes feed rate (millimeters per rev.) and $r_{\in}$ denotes tool nose radius (millimeters). Generally speaking, the theoretical date is less than the experimental date because of the violent vibration of machine tool structure during cutting process [21]. Figure 11 shows that the difference between the theoretical and experimental dates becomes less and less with feed rate increasing. The reason for that phenomenon is the slighter vibration of machine tool structure brought by the reduction of the adhered workpiece material and the thermal softening of the machined workpiece.

3.5 Influence of cutting parameters on surface microhardness with PCD tool

3.5.1 Influence of cutting speed

Figure 13 shows the progression of microhardness versus depth beneath the surface at two cutting speeds. The hardening rate at the cutting speed of 60 m/min is higher than that at the cutting speed of 30 m/min. It is possibly caused by enhanced cutting force at the high cutting speed. And, the higher cutting force also helps to form a thicker plastic deformation layer on the machined surface [7]. During the cutting process, the depth beneath the workpiece surface at which the minimum hardness forms is greater at the cutting speed of 60 m/min, compared with that at 30 m/min.

The depth beneath the workpiece surface at which the minimum hardness appears is lower at the initial cutting stage, compared with that at the middle cutting stage. The lowest hardness at the initial cutting stage is below the average hardness of the base material. The softening effect of the titanium alloy material is likely to be caused by aging process resulting from the high cutting temperature at the local surface [22]. And, the lowest hardness at the middle cutting stage is above the average hardness of the titanium alloy. Su and Che-

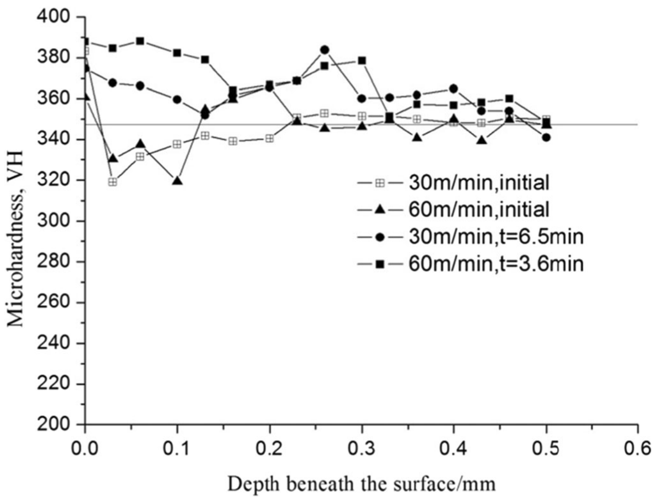


Fig. 13 Progression of microhardness at depth beneath the workpiece surface at two cutting speeds in machining with PCD tool (feed rate of 0.10 mm/r and cutting depth of 1.0 mm)

Haron [7, 22] found that nearly worn tools in machining of titanium alloy tended to increase the hardening rate of workpiece surface layer with PCD and tungsten carbide tools, respectively. The prolonged machining process results in the formation of the tool flank wear. The worn cutting tools increase cutting force and affect the microstructure to enhance the workpiece surface microhardness [22].

3.5.2 Influence of feed rate

Figure 14 shows the progression of microhardness versus depth beneath the workpiece surface at two feed rates. The microhardness at the feed rate of 0.10 mm/r is higher than that at the feed rate of 0.21 mm/r. From the above analysis, the reduction of the adhered workpiece material

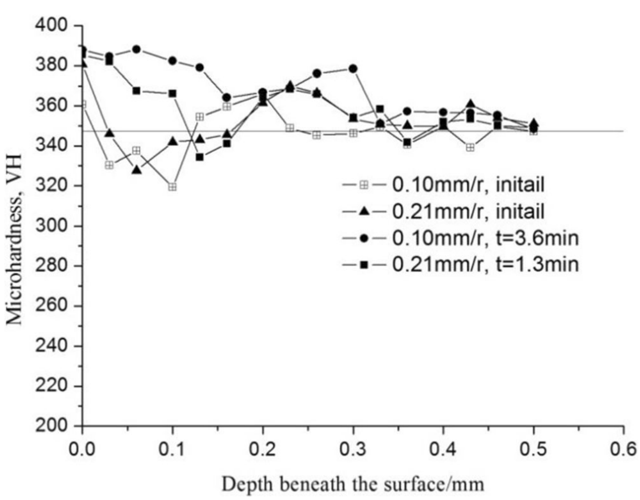


Fig. 14 Progression of microhardness at depth beneath the workpiece surface at two feed rates in machining with PCD tool (cutting speed of 60 mm/r and cutting depth of 1.0 mm)

on the tool surface and the thermal softening caused by high cutting temperature result in the formation of the decreasing cutting force at the feed rate of 0.21 mm/r. The low cutting force at the high feed rate results in the small work hardening rate. The depth beneath the workpiece surface at which the minimum hardness appears is observed to be lower at the feed rate of 0.21 mm/r than that at the feed rate of 0.10 mm/r. It is probably due to the explanation that the lower cutting force at the higher feed rate comes into being a thinner plastic deformation layer on the machined workpiece surface [7]. Besides, further machining of the titanium alloy after the initial machining stage increases the hardening rate of the machined surface layer.

4 Conclusion

1. During the machining Ti-6Al-4V alloy process, the strong diffusivity of PCD material led to the formation of the stable adhered workpiece material layer on the tool surface, resulting in a better performance of PCD cutting tool, compared with PCBN cutting tool. Specifically, the PCD tool possessed the better resistances to chipping and crater. The main failure mechanisms of the PCBN tool were chipping, notch, adhesion, and crater. The main failure mechanisms of the PCD tool were adhesion, crater, and dissolution-diffusion.
2. The life of PCBN tool was much shorter than that of PCD tool under the same cutting conditions. High cutting temperature and high cutting force made PCD insert drop from tool body under a high cutting speed after a long cutting time, so strengthening the joint strength between the PCD insert and the tool body was possible to be a way to prolong the PCD tool life and extend the applicable cutting speed range.
3. When the titanium alloy was machined with PCD tool, the reduction of adhered workpiece material on the tool surface at high cutting speed decreased cutting temperature at the cutting speed of 80 m/min. The decreasing cutting temperature led to a lower wear rate at the cutting speed of 80 m/min. When the cutting speed was beyond 60 m/min, workpiece surface roughness decreased with cutting speed increasing due to the decrease of adhered workpiece material. The increase of feed rate helped the decrease of the PCD tool life. The surface roughness initially increased, and after the feed rate of 0.1 mm/r, the reduction of the adhered workpiece material and the thermal softening made the surface roughness basically keep a constant value.
4. When the machining process was carried out with PCD cutting tool, the hardening rate of workpiece surface layer was higher under the condition of a high cutting speed,

while high feed rate resulted in a lower workpiece surface microhardness. Further machining after the initial cutting stage raised the hardening rate due to increasing tool flank wear.

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