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Tool Life and Surface Integrity in High-speed Milling of Titanium Alloy TA15 with PCD/PCBN Tools

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Abstract

Titanium alloys are widely used in aeronautics that demand a good combination of high strength, good corrosion resistance and low mass. The mechanical properties lead to challenges in machining operations such as high process temperature as well as rapidly increasing tool wear. The conventional tool materials are not able to maintain their hardness and other mechanical properties at higher cutting temperatures encountered in high speed machining. In this work, the new material tools, which are polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN) tools, are used in high-speed milling of Ti-6.5Al-2Zr-1Mo-1V (TA15) alloy. The performance and wear mechanism of the tools are investigated. Compared to PCBN tool, PCD tool has a much longer tool life, especially at higher cutting speeds. Analyses based on the SEM and EDX suggest that attrition, adhesion and diffusion are the main wear mechanisms of PCD and PCBN tools in high-speed milling of TA15. Oxidation wear is also observed at PCBN tool/workpiece interface. Roughness, defects, micro-hardness and microstructure of the machined surface are investigated. The recorded surface roughness values with PCD/PCBN tools are bellow 0.3 μm at initial and steady cutting stage. Micro-hardness analysis shows that the machined surface hardening depth with PCD and PCBN tools is small. There is no evidence of sub-surface defects with PCD and PCBN tools. It is concluded that for TA15 alloy, high-speed milling can be carried out with PCD/PCBN tools.

Keywords: high-speed milling; titanium alloys; cutting tools; wear; surface integrity

1. Introduction

Machining of titanium alloys has been a topic of great interest for industrial production and scientific research worldwide. Titanium alloys are widely utilized in the aerospace, biomedical, automotive and petroleum industries [1-2] due to their superior mechanical properties, heat resistance and corrosion resistance. One of the popular titanium alloys for these applications is TA15. This alloy was successfully developed in Russian in 1964. TA15 works well even at the temperature of 500 °C and it is the general alloy of bar stock and sheet material. So it has been chosen as the workpiece material in this study. It is generally considered that TA15 is a near-α titanium alloy of high aluminum equivalency, its strengthening mechanics is mainly solution strength of Al and other elements and it cannot be strengthened by heat treating. So TA15 alloy is used at annealed condition, where the phase composition of the alloy is the matrix α phase and a smaller volume fraction of the β phase.

However, titanium is very difficult to machine due to its poor machinability. During machining, conventional tools wear away rapidly because the poor thermal conductivity of titanium alloys results in higher temperature closer to the cutting edge and there exists strong adhesion between the tool and workpiece material[3]. In addition, titanium alloys are generally difficult to machine at cutting speed of over 30 m/min with high-speed steel (HSS) tools, and over 60 m/min with ce-

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mented tungsten carbide tools, resulting in very low productivity [4].

Therefore, over the years numerous research efforts have been made to improve the tool life by investigating tool wear and related issues to assist in choosing suitable machining conditions. According to the previous reports, advanced tool materials, such as PCBN and PCD, are being considered to achieve high-speed milling with the evolution of a number of new cutting tool materials. Some of the ultra-hard materials, such as polycrystalline diamond and cubic boron nitride (CBN) have been used in machining of titanium alloys [3, 5-7]. Wang et al. [8] had carried out an extensive study, showing that CBN tools have a remarkably long tool life under high-speed milling (up to 350 m/min).

Surface integrity is an important aspect of successful titanium machining. Good surface integrity is especially important in various engineering applications requiring high reliability and resistance to failure. It has been shown that the surface roughness is dependent on the tool material [6]. The surface roughness increased only marginally with an increase in tool wear for uncoated carbides, while this effect was pronounced when PCD inserts were used due to higher chatter observed at high cutting speeds. It is the basic requirement for high speed manufacturing to study and investigate the surface integrity characteristic of machined surfaces and sub-surfaces [9].

It is clear from these works that the PCBN and PCD are the most suitable cutting tool materials for titanium machining. The present work aims at comparing the performance of PCBN and PCD tools in machining TA15. The main objectives of the work are: 1) to compare the performances of PCBN and PCD tools in term of tool wear, tool life, and wear morphology to understand the underlying causes of the superior performance of PCD tools; 2) to investigate the influence of tool material on surface roughness and the quality of surface finish produced.

2. Experimental Procedures

2.1. Workpiece materials

The workpiece material used in the experiment was TA15 with chemical compositions shown in Table 1. Its mchemical properties are shown in Table 2.

Table 1 Chemical compositions of TA15

wt%

Al	V	Zr	Mo	Ti
5.5 –7.0	0.8 –2.5	1.5 –2.5	0.5 –2.0	Bal.

Table 2 Mechanical properties of TA15

Item	Value
Tensile strength /MPa	1 040
0.2% proof stress /MPa	855-959
Elongation /%	7-10
Modulus of elasticity /GPa	123
Hardness/HRC	40-44

2.2. Cutting tool materials

Machining was performed with a 20 mm diameter end mill tool holder fitted with our own tailor-made PCD/PCBN tools. Geometric parameters of two tools are shown in Table 3.

Table 3 Geometric parameters of two tools

Item	PCD	PCBN
Diameter/mm	20	20
Radial rake/ (°)	0	0
Clearance angle/ (°)	15	15
Corner radius/mm	0.4	0.4
Tooth number	2	2
Chamfer width/mm	0.10-0.15	0.10-0.15
Chamfer angle /(°)	–20	–20

2.3. Machining test

The experiments were conducted on a MICRON UCP710 machining centre with a maximum power of 16 kW and a maximum spindle speed of 18 000 r/min. The cutting conditions employed in this investigation were cutting speed 250 m/min and 350 m/min, feed 0.08 mm per tooth, axial depth of cut 3 mm and radial depth of cut 1 mm. Tool wear measurements of the insert were carried out using a microscope system. After a period of milling, the photo of the worn clearance face was taken by digital camera, and the flank wear VB was calculated automatically by the measure software.

The tool failure for rejecting a tool is often based on the following criteria: 1) the average flank wear or the maximum flank wear; 2) the crater wear depth; 3) breakage or fracture[10]. In this study, the maximum flank wear at the nose seemed to be the limiting factor that controlled the tool life in all cases. Hence, the average flank wear was chosen as the tool failure criterion, and the inserts were discarded when the average flank wear reached 0.40 mm or when catastrophic fracture of the edge was observed.

The surface roughness of the workpieces was measured by the aid of a stylus instrument. Surface roughness values of the workpieces were measured by MAHR-Perthometer M1 while measuring instrument and the measurements were repeated five times. To measure roughness of the surface of the workpiece, the cut-off length was taken as 0.8 mm and the sampling length as 5.6 mm.

The workpiece microstructure was examined with a MM-6 metallographic microscope. For the examination of microstructure alteration, the reagent was prepared with compositions 3% hydrogen fluoride, 6% nitric acid, and balance water. The specimens were etched by the reagent for about 10 s in order to ensure the microstructure of TA15. Hardness measurements were accomplished using a HXS-1000A digital microhardness tester with the test force of 0.245 N and duration time of 15 s. The micro-hardness measurement has been performed three times and the average values have been plotted.

3. Results and Discussion

3.1. Tool life

Average flank wear with cutting time of the two inserts is shown in Fig. 1, *v* is cutting speed.

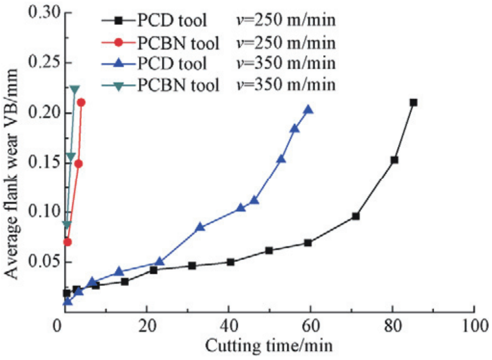


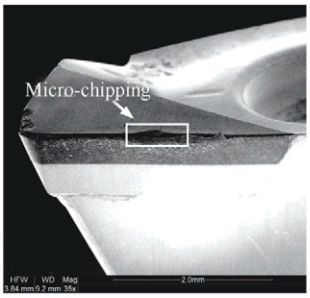
Fig. 1 Average flank wear vs cutting time of the two tools.

The tool life of PCD tool is much longer than that of PCBN tool under the same cutting conditions. From Fig. 1, it can be seen that the tool life of PCD tool is about 85 min when milling TA15 with a cutting speed 250 m/min, while at the same cutting condition, the tool life of PCBN tool is only about 6 min. With the increase of cutting speed, tool life is decreased. Tool life of PCD tool is 59 min with cutting speed 350 m/min, while at the same condition, tool life of PCBN tool is 3 min. It is possible that diffusion across the interface results in the formation of a titanium carbide layer which would then protect the tool in forming a barrier to further diffusion and loss of tool material in the chip. Some support from this contention can be obtained by using scanning electron microscope (SEM) with microanalysis facility[11] and observation that graphite crucibles are able to withstand attack by liquid titanium metal crucible[12] by forming a stable layer of titanium carbide on surface. However, this assumption requires further investigation. Nevertheless, it should be emphasized that the low wear rate of PCD is not at the expense of other machining parameters since the workpiece surface finish is always significantly better than that with other tool materials.

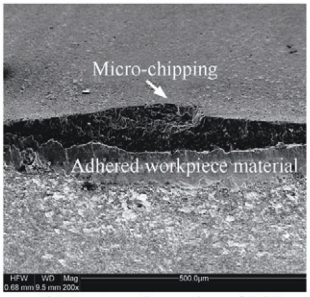
3.2. Tool wear

Figures 2-3 show the SEM analysis for the wear regions of PCD and PCBN tools in high-speed milling of TA15 alloy.

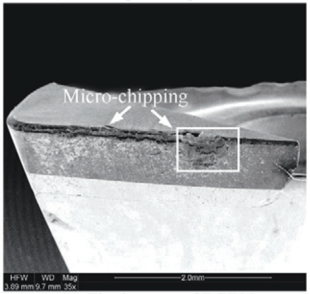
Fig. 2(b) and Fig. 2(d) show the rectangular regions of Fig. 2(a) and Fig. 2(c) with higher magnification, respectively. Non-uniform wear at the flank is found to dominate for two kinds of inserts. From Fig. 2(c), it can be observed that the notch wear dominates the tool wear mechanism of PCBN tool. This wear arises from the combination of high temperature and high cyclic stress, as well as the adhesion of the titanium workpiece onto the PCBN tool during the cutting process. CBN reacts with the titanium at high temperature and welds onto the tool edge. The attached tool material around is also forced off the tool when the welded material drops off from the tool edge, and hence the notch wear takes place. Adhesion of the workpiece materials onto the flank face of the two tools was also observed(see Fig. 2(b), Fig. 2(d), Fig. 3(b) and Fig. 3(d)), and it indicates that there is a strong bond at tool/workpiece interface. Since the cutting heat and cutting forces generated during the cutting process are higher under the given cutting conditions, it can be assumed that the higher temperature is the main reason that causes the adhesion of workpiece material onto the



(a) Flank wear of PCD



(b) Rectangular region of PCD



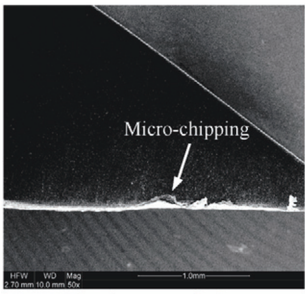
(c) Flank wear of PCBN

(d) rectangular region of PCBN

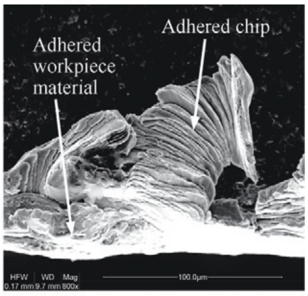
Fig. 2 SEM photographs of flank face.

flank and rake face. Cutting forces during the cutting process are also higher, resulting in higher stresses in the small contact region. The greater cutting temperature and stresses generated on the flank face close to the nose probably reduced the yield strength of the tools leading to higher wear.

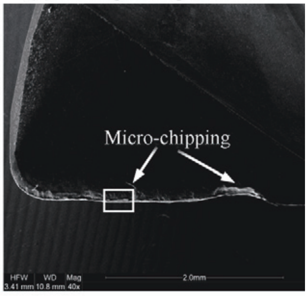
From Figs. 2-3, it can be observed that micro-chipping of two inserts occurred when machining titanium alloy. Micro-chipping occurred usually at the early stage of intermittent high-speed machining, because of the weakening of combination between CBN/diamond and binder due to the high temperature in high-speed machining.



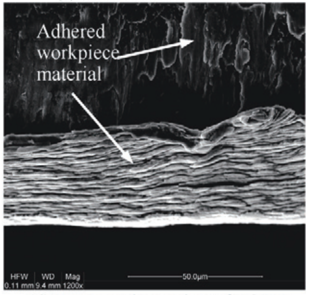
(a) Rake wear of PCD



(b) Rectangular region of PCD



(c) Rake wear of PCBN



(d) Rectangular region of PCBN

Fig. 3 SEM photographs of rake face.

Figures 4-5 show the EDX analysis of the flank face of PCD/PCBN tool which is etched with solution with 2% HF and 4%HNO_3 until the titanium alloy adhered on tools is removed absolutely. From Fig. 4, apart form boron, nitrogen and binder material cobalt, which are the main elements of PCBN tool, there are also some workpiece material elements, such as titanium and aluminum, on the etched flank face. Further quantitative analysis of Fig. 4 is shown in Table 4. Because the light element boron is absorbed seriously by SEM, its actual weight percentage is smaller than that in Table 4. So the actual weight percentage of titanium and aluminum are more than that in Table 4. Therefore, the transfer of workpiece material to PCBN tool has occurred. The chip/workpiece at temperature above 700 ℃ provides an ideal environment for diffusion of the tool material atoms across the tool/chip and tool/material interfaces[13]. Oxygen is also observed in Fig. 4. Under certain conditions, oxygen could react with CBN, which replaces nitrogen in the CBN and generates B_2O_3. It causes depression of the grain face and reduction of the grain edge, so the tool is not sharp. So oxidation wear of PCBN tool results in high tool wear.

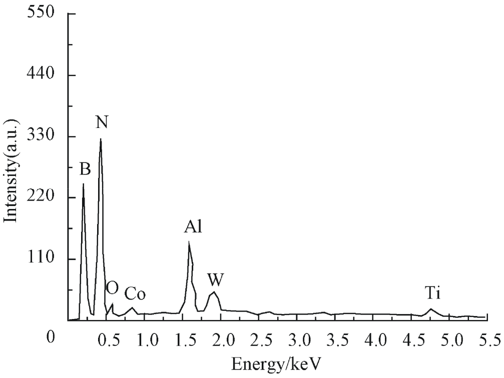


Fig. 4 EDX of etched flank face of PCBN

Table 4 Quantitative analysis of Fig. 4

Element	wt%	at%
B	67.49	75.36
N	26.52	22.85
O	00.93	00.70
Al	00.78	00.35
Ti	00.28	00.07
Co	02.92	00.60
W	01.09	00.07
Matrix	Correction	ZAF

Fig. 5 shows the EDX of etched flank face of PCD tool. The same diffusion wear can be observed in Fig. 5. Apart form carbon and binder material cobalt, which are the main elements of PCD tool, there are also some workpiece material elements, such as titanium and molybdenum, on the etched flank face. Further quantitative analysis of Fig. 5 is shown in Table 5. By quantifying the elements detected with EDX analysis, the weight percentage of titanium and molybdenum is 3.68% and 3.52%, respectively. Therefore, diffusion wear could occur at tool/workpiece interface. But oxygen is not found in Fig. 5, and oxidation wear does not exist at tool/workpiece interface.

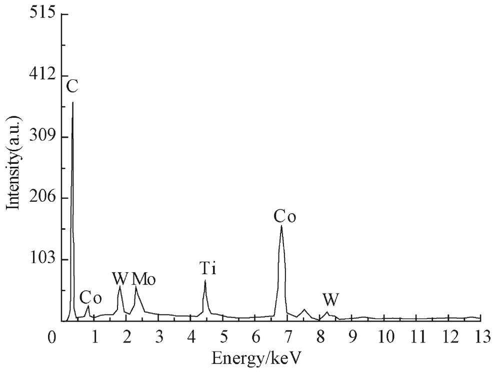


Fig. 5 EDX of etched flank face of PCD

Table 5 Quantitative analysis of Fig. 5

Element	wt%	at%
C	62.24	90.38
Mo	03.52	00.64
Ti	03.68	01.34
Co	23.56	06.97
W	06.99	00.66
Matrix	Correction	ZAF

3.3. Surface integrity

Average surface roughness values of machined surface with PCD and PCBN are shown in Fig. 6. Average surface roughness value of the machined surface in high-speed milling of TA15 with PCD tool is approximately 0.2 μm at the initial and steady stage, and increases to about 0.5 μm when tool wear reaches the tool life criteria. In the case of PCBN tool average surface roughness value is about 0.3 μm at the initial and steady stage, and increases to about 0.7 μm when tool wear reaches the tool life criteria. It is observed from Fig. 6 that the surface roughness with PCD tool is smaller than PCBN tool whether at the initial and steady stage or in the case that tool wear reaches the tool life criteria. At the initial and steady stage, surface roughness with PCD and PCBN tools is less than 0.3 μm such that no grinding or polishing would be required.

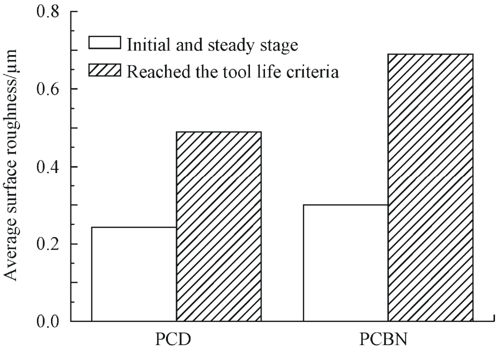
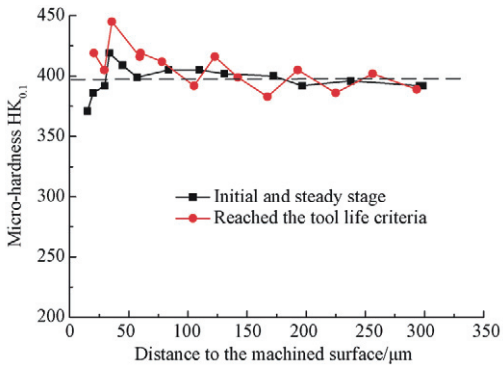
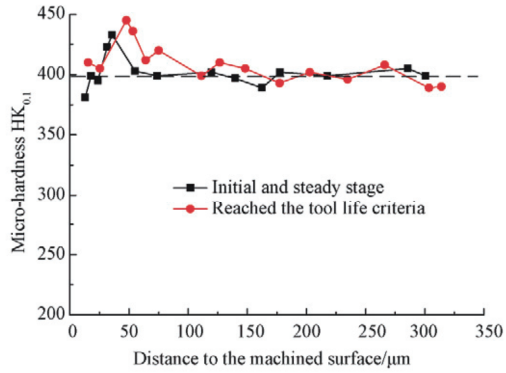


Fig. 6 Average surface roughness values of machined surface with the two tools.

Fig. 7 shows plots of micro-hardness values beneath the machined surface with PCD and PCBN tools, measured up to a depth of 350 μm below the machined surface. The hardness of the subsurface at 10 μm below the machined surface is below the average hardness recorded for the base material. The softening effect of the material at this level is probably due to over aging of titanium alloy as a result of very high cutting temperature produced at the local surface. The low thermal conductivity of titanium alloy also causes the temperature below the machined surface to be retained. The hardness value at 30 μm with PCD tool and at 40 μm with PCBN tool beneath the machined surface increases slightly. Hardening depth with PCBN tool is deeper than with PCD tool. It is probably due to that the wear rate of PCBN tool is higher than that of PCD tools which can be observed in Fig. 1. The wear on the cutting edge affects the microstructure, and the greatest surface hardening is found to take place when machining was carried with worn tools. Further machining of the titanium alloy with the nearly worn tools tends to increase the hardening rate of the surface layer. Figures 7(a)-7(b) show that higher values of hardness were recorded when tools reached the tool life criteria with PCD and PCBN tool, respectively.



(a) PCD

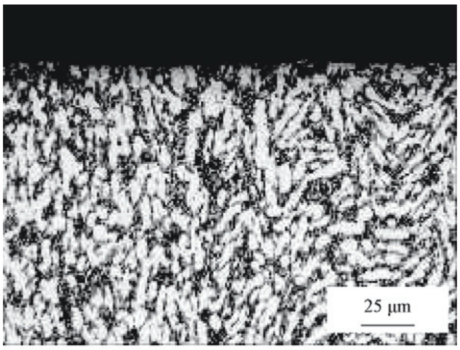


(b) PCBN

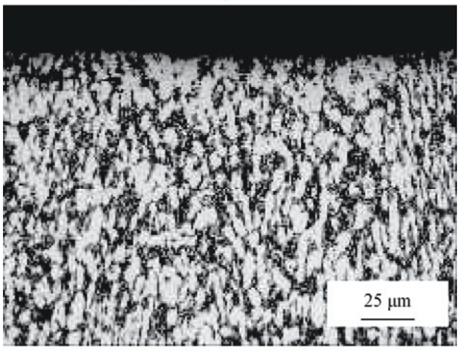
Fig. 7 Micro-hardness value beneath machined surface when machining with PCD and PCBN tools.

Figures 8-9 show the etched sections of machined surface perpendicular to the tool feed direction.

There was no evidence of sub-surface defects such as cracks, laps, visible tears of shear deformation after machining TA15 with PCD and PCBN tools. Figure 8



(a) Machining with PCD tool



(b) Machining with PCBN tool

Fig. 8 Microstructure of machined surface at initial cutting stage.

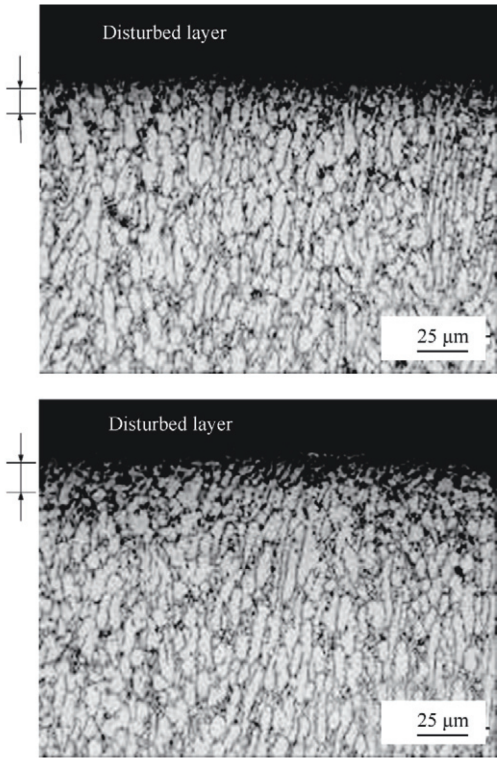


Fig. 9 Microstructure of machined surface when tool wear reaches the tool life criteria.

shows the smooth surface with less disturbed layer of the machined surface observed at the initial stage with PCD and PCBN tools. Prolonged machining with nearly worn tools produced severe plastic deformation and a thicker disturbed layer on the machined surface (see Fig. 9). Plastic deformation on the machined surface is caused by the high cutting pressure at elevated temperature during the machining process due to the low thermal conductivity of titanium alloy. However, since the surfaces were milled by PCD and PCBN tools with high coefficient of thermal conductivity and low friction coefficient, cutting temperatures are so low as to induce any phase transformations such as a white layer on the machined surfaces. It implies that no thermal damage occurred at the milling conditions.

4. Conclusions

From the observed performance of PCD/PCBN tools in high-speed machining of TA15 alloys, the following conclusions can be drawn:

1) The tool life of PCD is much longer than that of PCBN tools under the same cutting conditions in high-speed milling of TA15 alloys. Tool life of PCD tool is about 85 min when milling TA15 with a cutting speed 250 m/min, while at the same condition, tool life of PCBN tool is only about 6 min. With the increase of cutting speed, tool life is decreased. Tool life of PCD tool is 59 min with cutting speed 350 m/min, while at the same condition, tool life of PCBN tool is 3 min. PCD tool would be the most functionally satisfactory commercially available cutting tool material for machining titanium alloys.

2) Non-uniform wear at the flank is found to dominate for two kinds of inserts. The notch wear dominates the tool wear pattern of PCBN tool. Micro-chipping of two inserts occurs when machining titanium alloy. There is a strong bond at workpiece/tool interface, and the adhered workpiece material to the flank face is helpful in reducing wear rate. However, when the adhered workpiece material is subsequently removed, it will not only cause some removal of aggregate of tool materials, but also result in accelerated attrition wear on the flank face. Based on the EDX analysis of etched flank face of PCD/PCBN tool, dissolution of material from the workpiece by diffusion into the tool flank face takes place. It may cause diffusion-dissolution wear for PCD/PCBN tool. Oxygen is found on flank face of PCBN tool but PCD tool. Oxidation wear may exist at PCBN tool/workpiece interface and accelerate the tool wear.

3) Average surface roughness produced during machining using PCD insert is lower compared to that using PCBN insert, due to the effect of lower wear rate. At initial and steady cutting stage, average surface roughness value with PCD tool is about 0.2 μm, while that with PCBN tool is about 0.3 μm. With the increase of tool flank wear, surface roughness value is increased. Average surface roughness value with PCD tool is up to 0.5 μm, while that with PCBN tool is up to 0.7 μm when tool wear reaches the tool life criteria. Slight work hardening effect is observed, which increases with the increase of tool wear. It would not have any damage to the workpiece. Sub-surface defects such as cracks, laps, visible tears of shear deformation after

machining TA15 with PCD/PCBN tools are not observed. Worn tools produce severe plastic deformation and a thicker disturbed layer on the machined surface.

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Biography:

SU Honghua received Ph.D. from Nanjing University of Aeronautics and Astronautics in 2007, and then became a teacher there. His main research interest is mechanical manufacturing.

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