ORIGINAL ARTICLE

The performance of PCD tools in high-speed milling of Ti6Al4V

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Abstract Tool performance of conventional tools is poor and a major constraint when used in milling titanium alloys at elevated cutting speeds. At these high cutting speeds, the chemical and mechanical properties of Ti6Al4V cause complex wear mechanisms. In this paper, a fine-grain polycrystalline diamond (PCD) end mill tool was tested, and its wear behavior was studied. The performance of the PCD tool has been investigated in terms of tool life, cutting forces, and surface roughness. The PCD tool yielded longer tool life than a coated carbide tool at cutting speeds above 100 m/min. A slower wear progression was found with an increase in cutting speeds, whereas the norm is an exponential increase in tool wear at elevated speeds. Observations based on scanning electron microscope (SEM) and energy dispersive spectroscopy (EDAX) analysis suggest that adhesion of the workpiece is the wear main type, after which degradation of the tools accelerates probable due to the combined effect of high temperature degradation coupled with abrasion.

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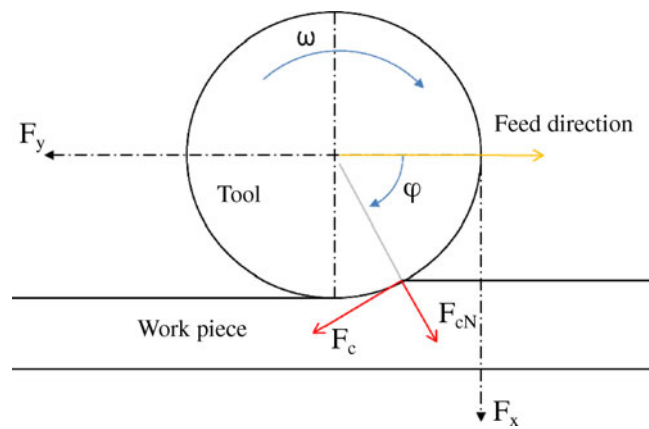Private Bag X1,
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1 Introduction

Titanium alloys have found wide application in the aerospace and biomedical industries due to their good strength-to-weight ratio and superior corrosion resistance [1]. High-speed machining is defined whereby conventional cutting speeds are exceeded by a factor of 5 to 10. Ti6Al4V is generally difficult to machine at cutting speeds of over 30 m/min with high-speed steel tools and over 60 m/min with cemented tungsten carbide tools [2]. The thermal conductivity [3] of Ti6Al4V (7 W/m K) is around 1/25 of that of aluminum (6061, 177 W/m K). The result is a concentration of heat in the cutting zone (thermal stress), causing the characteristically high tool wear for which titanium alloys are known [1, 3]. Temperatures [4] of 900°C have been measured at a cutting speed of 75 m/min. Titanium's chemical reactivity becomes problematic at temperatures above 500°C. Apart from diffusion wear, it has a strong affinity to adhere, which leads to chips seizing onto the tool cutting surface. Once a built-up edge develops, tool failure follows rapidly [5]. The combination of a low [6] Young's modulus (114 GPa) coupled with a high yield stress ratio allows only small plastic deformations [1–3] and encourages deflections, chatter, and movement of the workpiece away from the tool. The thermal conductivity for PCD ($\lambda \approx 400$ W/m K) is roughly four times greater than that of tungsten carbide ($\lambda \approx 100$ W/m K) [7], and PCD is significantly harder (approximately 6,000 HV) than carbides (approximately 2,500 HV). The softening temperature (hot hardness) [1] of PCD is higher than that of other commercially available cutting materials, indicating better performance at elevated temperatures [8]. Research [9] showed that PCD represents a substitute tool material for turning titanium alloys and that it produced a better

Table 1 Mechanical and physical properties of the workpiece at room temperature

Test specimen	Ti6Al4V
Hardness	360 HV
Ultimate tensile strength	1,080 MPa

workpiece surface integrity in finish turning operations [10]. Regardless of all these positive findings in turning, very little data exists on finish milling Ti6Al4V and even less on the rough milling using PCD. Studies [7] reported a tool life of 215 min (V_c=457 m/min) with PCD, concluding that high-speed milling of Ti6AlV4 is possible. Nurul Amin et al. [11] studied the effectiveness of PCD and compared it to uncoated tungsten carbide–cobalt inserts machining Ti6Al4V. The authors concluded that PCD inserts can be used effectively up to cutting speeds of 160 m/min, as the wear rate is relative low and the amount of metal removal per unit of tool life is acceptable. Similarly, research [3] reported a rather satisfactory long tool life (T=381 min) with good surface finish and geometrical accuracy, finish milling titanium compressor blades with PCD at a relatively slower cutting speed (V_c=110 m/min). In addition to this, research [2, 12] indicated that the performance of binderless cubic boron nitride (BCBN) is a manifestation of the phenomenon envisaged in a study [7], namely that a tool material with sufficiently hot hardness will be able to yield better machining productivity through the utilization of the thermal softening of Ti6Al4V by means of an α-β phase change [13]. This counterintuitive phenomenon has been discussed in the literature [7, 13], and it is believed [14] that higher cutting speeds lead to decreasing cutting forces [8] if the cutting material is able to maintain its hot strength, whereas the workpiece material softens at the cutting edge, and chips can be removed more easily. In addition, Eckstein et al. [15] describe a "slower wear progression" when working at high cutting speeds as compared to conventional milling, whereas the norm is an exponential increase in tool wear at elevated speeds. According to research, the wear mechanisms and mechanical issues of Ti6Al4V still require thorough study [16]. Furthermore, it is indicated [17] that additional research

Fig. 1 Schematic view of shoulder milling process

is required to determine the dominant tool wear mechanisms of PCD tool material. The objective of this work is to analyze the tool wear progression and the cutting forces variation relative to cutting speed. Similarly, the main wear types for PCD milling Ti6Al4V are studied.

2 Nomenclature

V_b	Flank wear land (μm)
V_c	Cutting speed (m/min)
f_z	Feed per tooth (mm/tooth)
h_{ex}	Maximum chip thickness (mm)
F_x, F_y, F_z	Force components in x-, y-, and z-directions (N)
F_c, F_{cN}, F_a	Cutting, cutting perpendicular, and axial force components (N)
k_c	Cutting coefficient (N/mm^2)
a_e, a_p	Radial- and axial depth of cut (mm)
θ	Engagement angle (degree)
ω	Spindle rotational speed (rev/min)
φ	Instantaneous angle position of the shoulder mill with respect to the negative y-direction and measured clockwise (degree)
φ_{st}	Entry angle of tool (degree)
φ_{ex}	Exit angle of tool (degree)

Table 2 Milling conditions and parameters of experiments

Parameter	Condition
Cutting speed (V_c)	100–500 m/min
Feed/tooth (f_z)	0.025, 0.0375, and 0.05 mm/z
Depth of cut (a_p)	2 mm
Working engagement (a_e)	0.5 mm
Coolant	Flood

3 Experimental procedure

3.1 Work material

A Ti6Al4V (ASTM B265, grade 5) sample was used, with a hardness measured to be 360 HV and a high ultimate tensile strength (1,080 MPa) as indicated in Table 1. This grade of

Fig. 2 Wear progression of PCD at different cutting speeds (f_z=0.05 mm/z)
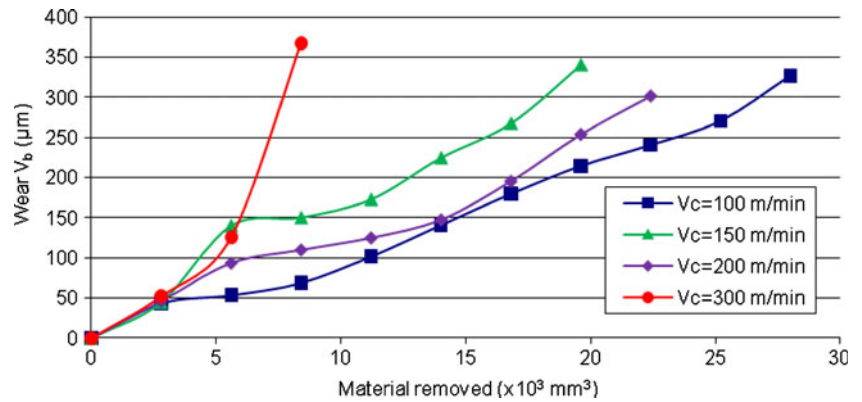
material was chosen to produce the most demanding conditions achievable when machining this alloy.

3.2 Milling experiment

Research [18] suggested a cutting speed in the range of 185 to 220 m/min for titanium alloys and the chip load (f_z) below 0.05 mm [7] to reduce the possibility of catastrophic tool failure in climb milling. Table 2 tabulates the cutting conditions for the experiments.

Experiments were done at cutting speeds ranging from 100 to 500 m/min and feed rate of 0.025–0.05 mm/z. A Hermle C40U milling machine was used with a lubrication emulsion designed specifically for the cutting of titanium alloys. Due to the low modulus of elasticity of the workpiece, the length was limited to 280 mm, in order to ensure rigid clamping of the material to minimize vibration. The PCD (CMX850) tools were examined after set cutting intervals, and the wear was continuously observed. The performance of the PCD was compared to that of coated carbide. The flank wear land (V_b) was analyzed with an optical microscope for dimensional measurements. The SEM was used for wear characterization, and the surface roughness was measured with a digital

surface roughness meter. The failure criterion due to wear on the flank [11] was set for a maximum when V_b=0.3 mm, and R_a=1.6 μm [8] was used for surface roughness. Cutting forces are determined by the machined cross-section width and thickness, the cutting speed, and the tool wear. Figure 1 is a schematic view illustrating the experimental setup.

Once the force components in the x-, y-, and z-directions were measured with a Kistler 9255B dynamometer, F_c, F_R, and F_a could be expressed by the following transformation [19]:

$$\begin{bmatrix} F_c \\ F_{cN} \\ F_a \end{bmatrix} = \begin{bmatrix} -\sin\varphi & \cos\varphi & 0 \\ \cos\varphi & \sin\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \qquad (1)$$

The entry angle of the tooth in the down milling operation, starting from the negative y-axis should be

$$\varphi_{st} = 90° - \cos^{-1}[(R - a_e)/R] \qquad (2)$$

The tooth exits the cutting segment at an angle of approximately φ_{ex}=90°, and the chip thickness is

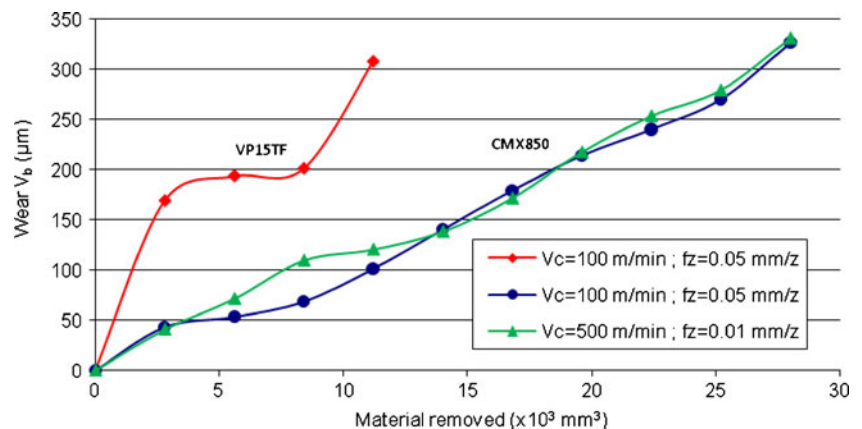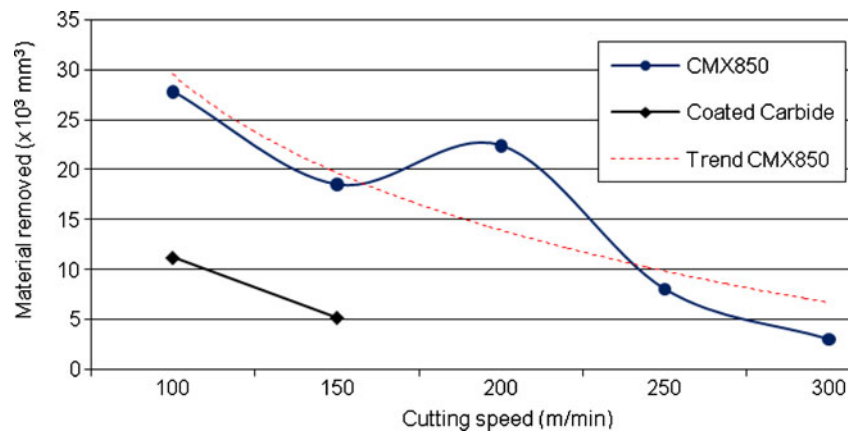**Fig. 3** Tool life of PCD compared to the coated carbide at elevated cutting speeds

Fig. 4 Tool life of PCD and coated carbide (f_z=0.05 mm/z)

zero at this point. Thereby, Eq. 1 can be modified as follows:

$$\begin{bmatrix} F_c \\ F_{cN} \\ F_a \end{bmatrix} = \begin{bmatrix} -\sin\varphi & \cos\varphi & 0 \\ \cos\varphi & \sin\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \text{ when } \varphi_{st} < \varphi < \varphi_{ex}$$

$$(3)$$

The cutting coefficients (k_c) may be considered as a constant with respect to cutting speed for conventional cutting speeds, but under high-speed conditions, the value may decrease or increase due to thermal softening or strain rate hardening, respectively, as per Eq. 4 [20]:

$$k_c = \frac{F_c}{h_{ex} \times a_p} \qquad (4)$$

4 Results and discussion

4.1 Tool life

The tools were examined after set cutting intervals, and the wear was continuously observed. The V_b was analyzed with

an optical microscope for dimensional measurements, and the SEM was used for wear characterization. PCD was compared with a commercially available coated carbide material. The PCD performed satisfactorily for cutting speeds in the range of 100–200 m/min with f_z=0.05 mm/z. As shown in Fig. 2, an increase in cutting speed resulted in sudden tool failure, because of the significant reduction in the strength and hardness of the tool material at elevated temperatures.

Lowering the feed rate to 0.01 mm/z and increasing the cutting speed to 500 m/min enabled the PCD to cut for similar extended tool life as when cutting at 100 m/min (f_z=0.05 mm/z), and a distinctly better surface finish was attained. The surface roughness measurements for the different cutting speeds all resulted in R_a<1. At elevated cutting speeds, the PCD outperformed the benchmark coated carbide, which is illustrated in Fig. 3.

The failure of the coated carbide in the high temperature environment could be due to the lower hot hardness of the tool as depicted in the literature [1, 2]. Figure 3 indicates the generally accepted decreasing trend in tool life, associated with an increase in cutting speed. For tool

Fig. 5 Measured cutting forces at different cutting speeds (f_z= 0.05 mm/z)
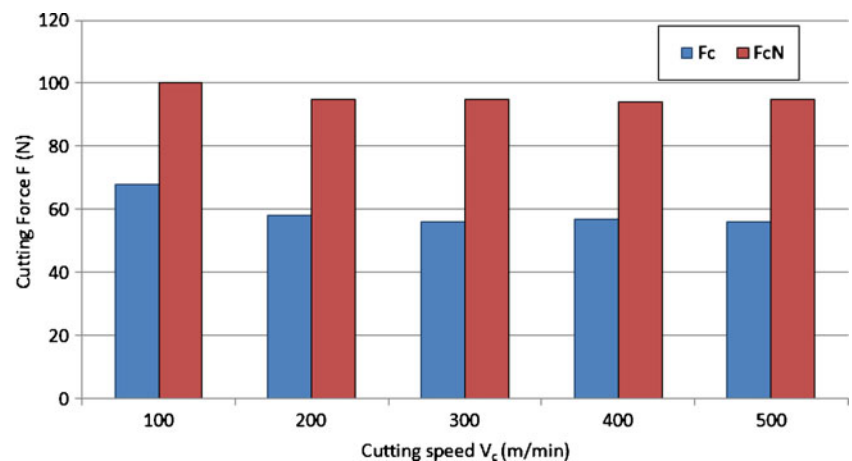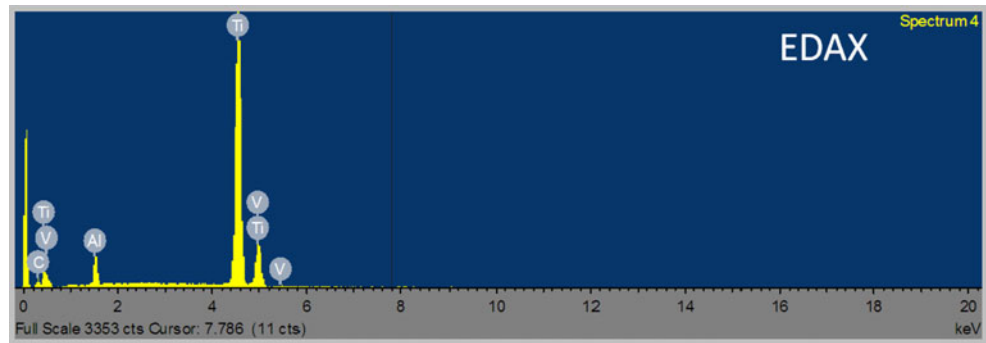
materials with lower transverse rupture strength, such as PCD compared to carbide, there may be a minimum cutting speed below which mechanical overload may occur. In the same way, a local maximum tool life may exist if there is a phase change in the workpiece material, and the insert can withstand the harsh operating conditions associated with the elevated temperature. This PCD proved that there is a definite increase in tool life, at a cutting speed of 200 m/min (f_z=0.05 mm/z) compared to 150 m/min (Fig. 4).

In this study, the tool life increased when the cutting speed was increased from 150 to 200 m/min. The literature shows that increasing the cutting speed beyond 200 m/min will increase the cutting temperature significantly beyond 1,000°C [21]. The α phase (hexagonal close packed) of Ti6Al4V is hard and brittle, with a strong hardening tendency. The β phase (body-centered cubic) is ductile and can be cut more easily, but also has a strong tendency to adhere [3]. The body-centered cubic structure has more slip systems, thereby reducing the yield stress for failure in shear [13]. Also, considering that the strength of Ti6Al4V is reduced from 1,000 MPa at ambient temperature to below 550 MPa above 500°C [6], the explanation for this increase in tool life could be the phase transformation from α to β phase, which occurs at about 950°C and above [22]. At a cutting speed of 250 m/min, the tool life was significantly reduced. Although the strength of the workpiece material is low at this cutting speed [22], the chemical attack on the tool is more aggressive. Thermal softening and chemical reactions weakened the intergranular bonds of the cobalt and diamonds in the PCD tool, which caused the grains to tear apart under the action of the machining shear stress.

Table 3 SEM EDAX analysis of the material build-up on the PCD tool material; as supporting evidence, the build-up is Ti6Al4V

In stats	C	O	Al	Ti	V	Total
Weight %	3.95	–	5.34	86.9	3.81	100

4.2 Cutting forces

Cutting is a process of extensive stresses and plastic deformations. The high compressive and frictional contact stresses on the tool face result in substantial cutting force. Figure 5 illustrates the F_c for the different cutting speeds.

Similar to literature [1, 2, 8, 12], the cutting force decreased with an increase in V_c for CMX850. There is a noticeable reduction in cutting force when increasing the cutting speed from V_c=100 to V_c=200 m/min. This is at the same cutting speed that resulted in slower wear progression with an increase in cutting speed. This step decrease in k_c from 2,400 N/mm^2 (V_c=100 m/min) to 2,085 N/mm^2 (V_c=200 m/min) might be due to the new slip system after the phase change. A clear minimum of all cutting force components is discovered when finishing with V_c=300 m/min.

4.3 Observations of tool wear

SEM analysis was also employed in order to identify the build-up on the flank wear scar. The build-up on the PCD material was found to be Ti6Al4V. Figure 6 illustrates the results of this analysis. Compared with the nominal 6% aluminum and 4% vanadium in Table 3, it becomes clear that the deposit is work material.

This was supported using image mapping with the SEM and its software as shown in Fig. 7.

An EDM sectioned sample gives an indication of the formed wear scar on the flank. Figure 8 indicates where the sample was cut and the form of the wear scar. The sample was ×350 enlarged under the SEM.

As illustrated, the PCD tool was cut through the wear scar (section A-A) by means of electric discharge machining (EDM) and polished. The SEM on the sectioned sample yielded supportive information to establish that the depth of the wear on the flank to be around 20–25-μm deep. Acid cleaning (hydrochloric acid) enabled that the true wear scar was exposed below the deposited Ti6Al4V layer on the flank. Post-acid cleaning SEM analysis revealed that a

Fig. 7 Analysis of material build-up on the PCD using image mapping with the SEM, showing that the build-up is Ti6Al4V on the PCD tool material
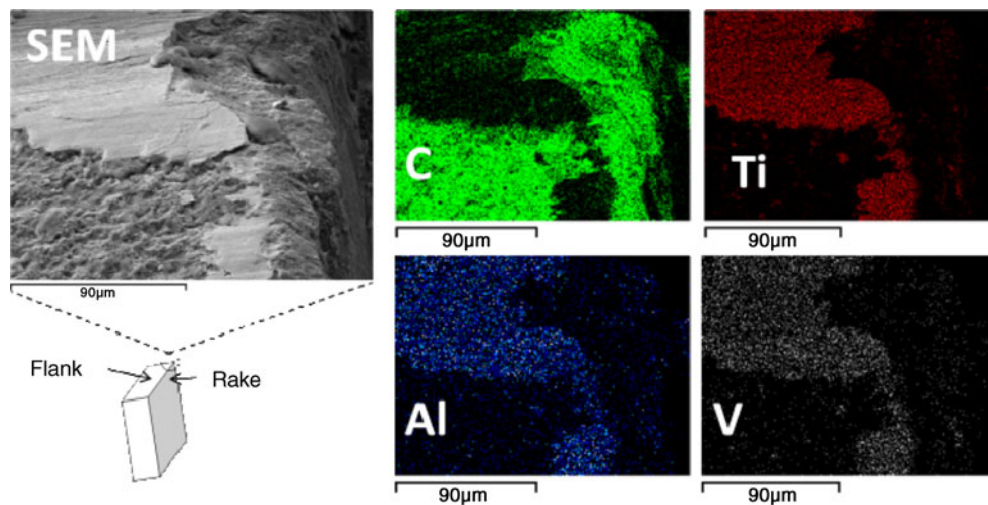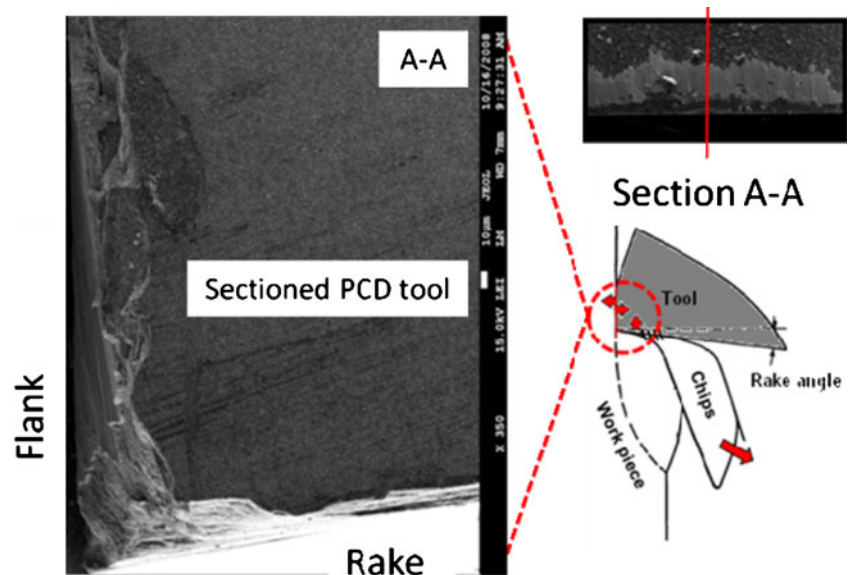

Fig. 8 EDM sectioned wear scar showing the depth of the wear on the flank

typical flank wear scar had different wear regions as illustrated in Fig. 9.

These different regions from the edge inward are as follows:

Region A: The highest load is exerted on the edge of the insert. This zone is where the initial chipping occurs, due to mechanical impact, and is measured to be around 45-μm deep with the SEM.

Region B: This region is also characterized with impact-related wear. The workpiece material tends to stick and break away under the cutting forces. This causes small particles to be gradually dislodged out of the diamond matrix.

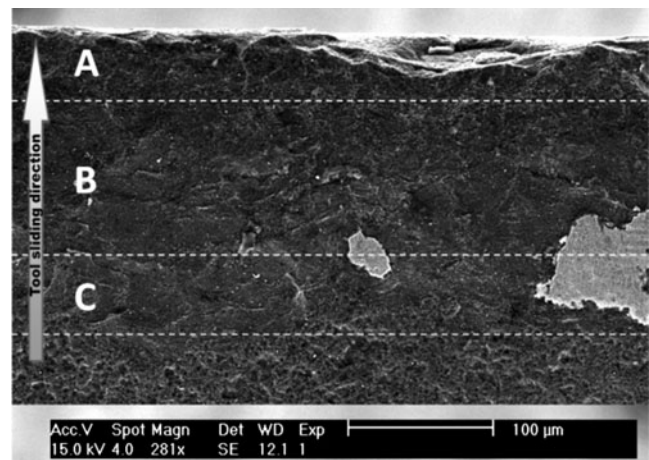Region C: This region was covered with a Ti6Al4V layer, and the region is characterized by a relatively

Fig. 9 Etched PCD wear scar on the flank illustrating the different wear regions

smoother (polished) surface. The removed and adhered layers caused more adhesive rubbing, which is believed to increase the cutting temperature. This causes the workpiece to weld onto the wear scar. The critical temperature for adhesion to occur for machining with PCD is reported [23] to be roughly 760°C, around which, the high temperature strength of PCD is believed [1] to be degrading as well. Also above 800°C, the probability of chemical interaction of PCD with the workpiece material [6] increases.

5 Conclusion

The performance of PCD tools have been investigated in terms of tool life, surface roughness, cutting forces, and the wear mechanisms under different cutting conditions. Results from this study showed that for PCD, a decrease in feed and an increase in cutting speed (V_c) produced a better surface finish, while achieving a similar tool life when compared to lower speeds and higher feeds. PCD has outperformed the carbide tool at elevated cutting speeds. Complementary to the slower wear progression that was found at a cutting speed 200 m/min, the cutting force was also reduced by a significant amount. Observations based on SEM analysis suggested that adhesion of the workpiece took place during milling of Ti6Al4V, after which, degradation of the tool accelerated, probably due to the combined effect of thermal and mechanical wear.

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