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Failure mode analysis of carbide cutting tools used for machining titanium alloy

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Abstract

Intensive research on the performance of coated carbide tools in machining titanium alloy is being conducted worldwide. Titanium alloy has special characteristics such as high strength at elevated temperature and high mechanical resistance that makes carbide tools suitable to cut this material. This is because carbide tools are classified as hard and highly resistant to wear even at high temperature. This paper discusses the failure mode of a coated carbide cutting edge that is caused by the loading and unloading effect during milling. Tool failure adversely affects tool life, the quality of the machined surface and the surface's dimensional accuracy, and consequently the economics of cutting operations. The milling parameters that were observed to affect the failure of coated carbide tools were cutting speed, feed rate, depth of cut, and the application of a cutting fluid. Wear occurred along the flank and rake faces, which then propagated into the substrate material after the removal of the coating material. Wear along the flank and rake faces led to the concentration of stress over a certain area of the cutting edge, which was initiated by a microcrack and then propagated due to the loading and unloading effect during the intermittent milling process until significant brittle fracture occurred in the substrate material. Cutting speed and depth of cut were identified as the main factors responsible for the failure and fatigue of the coated carbide tools during the milling of titanium alloy.

Keywords: Failure mode; Coated carbide tool; Milling process; Titanium alloy

1. Introduction

Currently, machining and manufacturing industries greatly emphasise the importance of developing products accurately, rapidly and in a cost-effective manner. Machining processes that involve high cutting speeds and feed rates will adversely affect the cutting edges used and induce rapid wear rates [1]. According to Benedict et al. [2], Donaldson et al. [3] and Ghani et al. [1], milling is one method that can be used to remove material by moving the work material and rotating the cutting tool. This process produces flat or contoured surfaces of various configurations. In addition, when the work piece changes, the position, cutting tool geometry, and cutting force will also be changed [1].

Titanium alloy is known as a material that is difficult to machine, particularly due its low thermal conductivity [4]. Furthermore, the limitations of machining titanium alloy are due to the fact that the material is difficult to shape, even though it has good mechanical properties such as a high strength-to-weight ratio, resilience at high temperature, corrosion resistance and longer service life span compared to other composite materials [4–6].

There are various types of cutting tool materials currently on the market for use in machining, including carbide, high-speed steel, cast cobalt alloy, ceramic-based

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alumina, diamond and others. The application of these cutting tool materials depends on the type of work materials to be cut, such as titanium, cast iron, hardened tool steel and others [1]. In the machining industry, carbide-based cutting tools have been the most extensively used tool since they were introduced in Germany in the 1920s to fulfill the high-wear-resistance requirement of the mould industry [7]. Carbide-based cutting tools are produced from the mixture of a carbide compound and a soft, ductile metal binder. This mixture is compressed before being sintered, making the resulting material hard and highly resistant and resilient to heat. Cutting tools composed of tungsten carbide (WC) with a cobalt (Co) binder were the first to be fabricated in the industry. Another name for this substance is straight tungsten carbide. This material is suitable for machining cast iron and non-metallic materials. By controlling the powder size of the WC and Co components, the composition of WC–Co can be varied to obtain materials with various combinations of abrasive resistance and strength [7].

According to Ozel and Nadgir [8], it is very important to be able to predict and detect the wear on a cutting edge before it scratches a machined surface to prevent the generation of scrapped products due to a worn-out cutting edge and consequently enhance productivity. Furthermore, the ability to predict various types of wear mechanisms is very important to the design of better cutting tool materials. This notion is also supported by Arsecularatne et al. [9]. According to Arsecularatne et al., the ability to predict a cutting tool's lifetime during machining is important to cutting tool design and determining suitable cutting methods that do not adversely affect machining performance and cost. Ginting and Nouari [10] found that the lifetime of uncoated carbide tools was extended at low cutting speeds (60 m/min); however, at high cutting speeds, coated carbide tools performed better.

Failure is the result of the wear process during machining. According to Ginting and Nouari [10], brittle fracture and plastic deformation are caused by an excessively high wear rate at the edge of a cutting tool. Both effects can be avoided by using suitable cutting parameters. Brittle fracture is induced by a small area of solid fracture or a slight change in plastic deformation that cannot be seen by the naked eye. This type of fracture is normally accompanied by rapid crack propagation. Broken surfaces appear shiny, smooth and wedged [11]. Brittle fracture can be induced by plastic deformation, and sometimes cup- and cone-shaped broken surfaces are produced [11]. Ductile fracture refers to the process by which a metal is torn, which is followed by slow crack propagation and plastic deformation. Ductile fracture surfaces appear rough and fibrous.

This paper presents the analysis of the failure mode of a coated carbide cutting edge caused by the loading and unloading effect during the milling of titanium alloy. In this study, the type of failure experienced on and beneath the surface of a coated carbide tool after machining titanium alloy was investigated in detail. This analysis will help cutting tool manufacturers to improve the properties of cutting tool materials and thereby enhance the lifetime of cutting tools used to machine titanium alloy.

2. Methodology

2.1. Milling process

This experiment was conducted to study the effect of machining parameters on the wear mechanism and failure mode of coated carbide cutting tools when milling titanium alloy. Machining trials were carried out on a Haas 3-axis milling machine. The cutting tool investigated was a 10 mm round insert PVD-coated carbide tool, as shown in Fig. 1. The chemical composition, physical and mechanical properties, and geometry of the insert and the physical properties of the coating are presented in Tables 1–4, respectively.

Titanium alloy from the alpha–beta group Ti–6Al–4V was selected in this study due to its wide use in the aerospace industry. The composition (wt%) and the mechanical properties of this material are presented in

Fig. 1. PVD coated carbide insert with tool holder.

Table1
Chemical composition, physical properties and geometry of the insert.

Composition	WC	Co
Wt%	87	13

Table 2
Physical and mechanical properties of the insert.

Particle size	Hardness at 25 °C	Density	Elastic modulus	Thermal expansion rate
0.8 μm	1470 HV_{10}	14.5 g/cm^3	580 Gpa	$5.5 \times 10^{-6}\ K^{-1}$

Table 3
Insert geometry.

Cutting rake angle	Axial rake angle	Radial rake angle
−4° to 0°	+6°	−4° to 0°

Table 4
Physical properties of the coating.

Type	Material	Thickness	Melting point	Hardness at 25 °C
Physical vapour deposition	TiN, TiCN, TiALN	≅4 μm	≅3070 °C	2300 HV_{10}

Table 5
Composition (wt%) of Ti–6Al–4V.

Content	O	H	N	C	Fe	V	Al	Ti
wt%	–	0.005	0.01	0.05	0.09	4.40	6.15	Balance

Table 6
Mechanical properties of Ti–6Al–4V at room temperature.

Tensile strength (MPa)	Yield strength (MPa)	Density (kg/m^3)	Modulus of elasticity (GPa)	Hardness (HRC)
993	830	4540	114	36

Tables 5 and 6, respectively. The dimensions of the Ti–6Al–4V test piece were $100 \times 100 \times 160\ mm^3$. The milling parameters studied are presented in Table 7. This range of parameters was chosen to evaluate the ability of the carbide tool to withstand high cutting speeds with minimum quantity lubricant (MQL).

The wear on the tool's flank face was measured after the first pass using a tool maker's microscope equipped with a graduated scale in millimetre. Thus, the wear measurement depended on the wear rate. The parameter measured to represent the extent of wear was the maximum tool wear VB_{max}. Machining was stopped when $VB_{max}=0.3$ mm.

2.2. Sample preparation for tool failure mode analysis

The worn out cutting tool specimen was cut into small pieces by a diamond cutter model ISOMET® 1000. All the samples were mounted on a mould with a bakelite mixture at 160 °C. The specimen was ground and polished using a semi-automatic polishing unit. Rough grinding was performed on wet metallographic grinding paper with a grit size of P240, followed by grinding with paper possessing grit sizes of P400 and P600. These grits were selected because they could remove a minimum material thickness of approximately 0.05 mm (0.02″). The grinding was then continued using a 3 μm polycrystalline diamond suspension. Finally, a colloidal silica polishing suspension was used to obtain a mirror-like surface. Then, the sample was etched using a solution containing 15 mL water, 30 mL HCl, 15 mL acetic acid and 15 mL HNO_3. After etching, the sample was observed under a scanning electron microscope to investigate the failure mode of the specimen in detail.

3. Result and discussion

3.1. Tool life and wear mechanism

Worn-out cutting tools limit the cutting speed and feed rate applied [1]. The performance of a carbide tool not only depends on the type and number of coating layers applied but also on the size of the carbide particles and the number of binders. Information regarding porosity, particle size and WC bond, carbide solid solution and metal binder can be obtained by polishing a sample [11].

In this study, the tool life, measured in distance travelled by the tool, was found to decrease with the cutting speed. A long tool life of 2300 mm was achieved when machining at a cutting speed of 120 m/min, whereas a tool life of only 1200 mm was achieved when machining at 135 mm/min. In other words, the application of a cutting speed in the range of 120–135 m/min caused the tool life to drastically decrease. Figs. 2 and 3 show similar chipping wear mechanisms; chips that stick to the cutting edge in this range of cutting speeds limit tool life. This occurred at high cutting speeds due to the generation of large amounts of heat in the cutting zone. This consequently weakened the strength of the cobalt bond, which then led to the removal of the tungsten carbide particles from the cutting edge. This was the main cause of tool wear and other tool failure modes, as also indicated by previous researchers [4,10]. Therefore, cutting tool life should be predicted based on the wear rate and also on the properties of the machined surface produced. The generation of heat and ultimate weakening of the cobalt bond were the results of the direct and indirect effects of the cutting force and cutting temperature, which are commonly associated with the machining parameters considered [10]. According to Shaw [12], the feed rate was the main factor that affected the cutting force and cutting temperature during the milling of titanium alloy. In addition, Ginting and Nouari [10] found that chip formation during machining was the main cause of heat generation in the cutting zone.

Md Said [13] also observed a decrease in cutting tool life with an increase in the feed rate, though in the presence of a cutting fluid. Although the effects of the feed rate were weaker than those of the cutting speed, the feed rate is still one of the most significant factors determining tool life. This is because the shearing zone area during chip formation increases proportionally with the feed rate.

3.1.1. *Failure mode of carbide cutting tool at cutting speed of 120 m/min*

Machining at a cutting speed of 120 m/min resulted in the failure of the cutting tool, as shown in Fig. 4. The cutting edge was fractured and cracked after the removal of the coating material. Thus, the geometry of the cutting edge was altered. From these figures, it is clearly observed that the failure by brittle fracture can be divided into three zones: A, B, and C. Higher-magnification images of zones A, B, and C are shown in Figs. 5–7, respectively. Fig. 5 shows an early crack that may have been generated by the concentration of stress induced by the sudden load applied to the cutting edge; this may have led to the brittle fracture observed along the cutting edge. This area is very close to the fracture region. This phenomenon was also observed by Trent [14] and Haron and Jawaid [5]. In their studies, brittle fracture was attributed to the early formation of a crack in an area of high-stress concentration, in particular, at the nose of the cutting tool.

Fig. 6 shows an initial microcrack in zone B before total fracture occurred as shown in Fig. 7. In Fig. 7, brittle fracture occurred due to the weakening of the micro bonding between the tungsten carbide particles and their binders.

Fig. 7(a) and (b) shows a tungsten carbide particle that was loosened from the binder and chipped from the cutting tool. This phenomenon confirms that the cutting edge experienced brittle fracture. According to Trent [14], a cutting edge surface possessing cracks will lead to chipping and brittle fracture.

3.1.2. *Failure mode of carbide cutting tool at cutting speed of 135 m/min*

The failure mode experienced by the cutting edge at a high cutting speed of 135 m/min is categorised as catastrophic failure [15]. The main cutting edge was completely fractured as shown in Fig. 8. This phenomenon was directly associated with a wear mechanism as a result of the high cutting temperature generated during the machining process. Furthermore, it may be due to mechanical impact, transient thermal stresses, and excessive crater and flank wear [16]. The results show that the type of carbide tool under investigation is not suitable for machining titanium alloy above a cutting speed of 120 m/min. A similar conclusion was drawn by Jianxin et al. [16], who observed the complete breakdown of their tool tip and cutting edges when machining Inconel718 nickel-based alloys at 180 m/min. Thus, the tools used are not suitable for machining Inconel718 nickel-based alloys at cutting

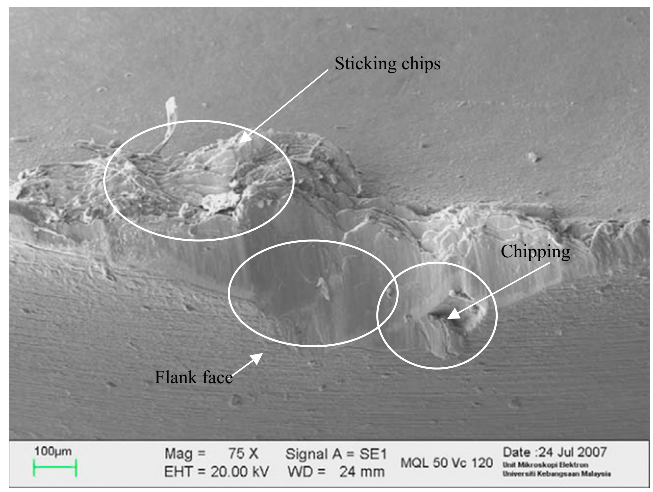

Fig. 2. Wear mechanism at cutting speed of 120 m/min, MQL 50 mL, feed rate 0.1 mm/tooth, and depth of cut 2 mm.

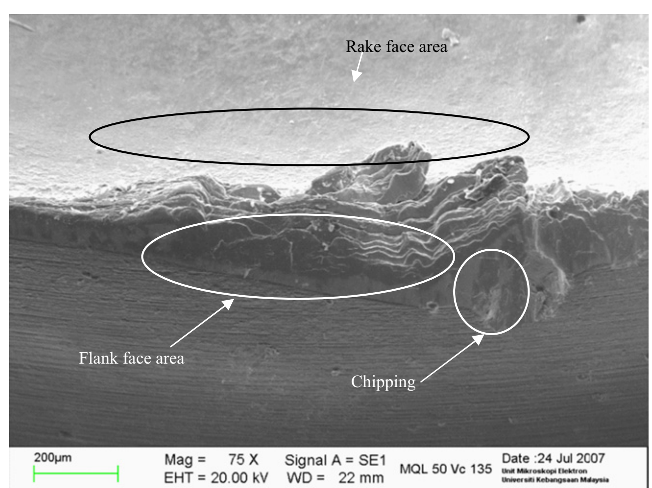

Fig. 3. Wear of flank face and rake face areas at cutting speed of 135 m/min and MQL 50 mL/J, feed rate 0.1 mm/tooth, and depth of cut 2 mm.

Table 7
Milling parameter.

Cutting speed (m/min)	MQL (mL/J)	Feed rate (mm/tooth)	Depth of cut (mm)
120	50	0.1	2
135	50	0.1	2

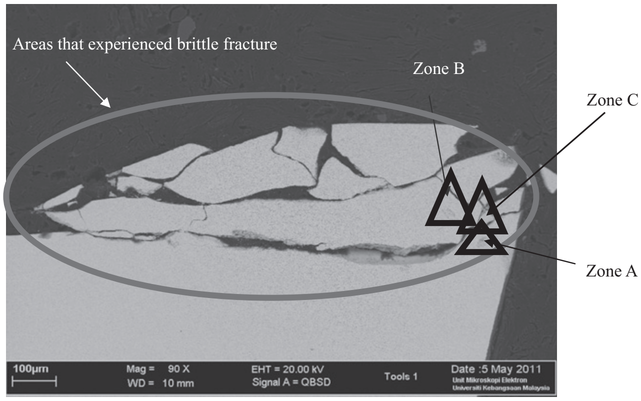

Fig. 4. Failure mode on the cutting tool when machining at cutting speed of 120 m/min, feed rate of 0.1 mm/tooth, depth of cut 2 mm, and MQL 50 ml/J.

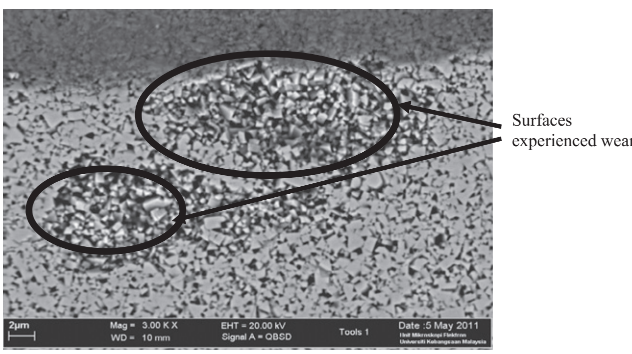

Fig. 5. Higher magnification of zone A.

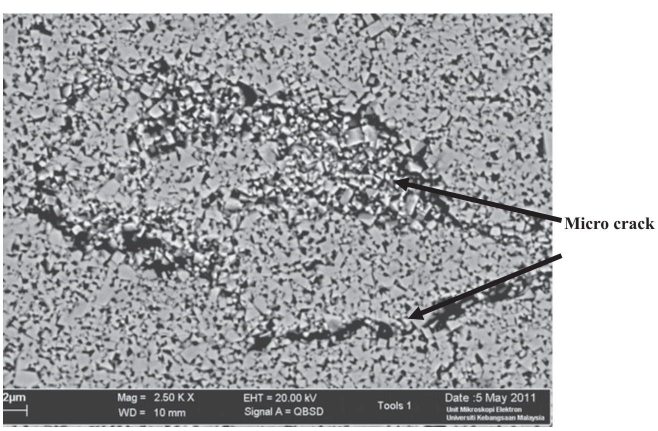

Fig. 6. Higher magnification of zone B showing the initial microcrack.

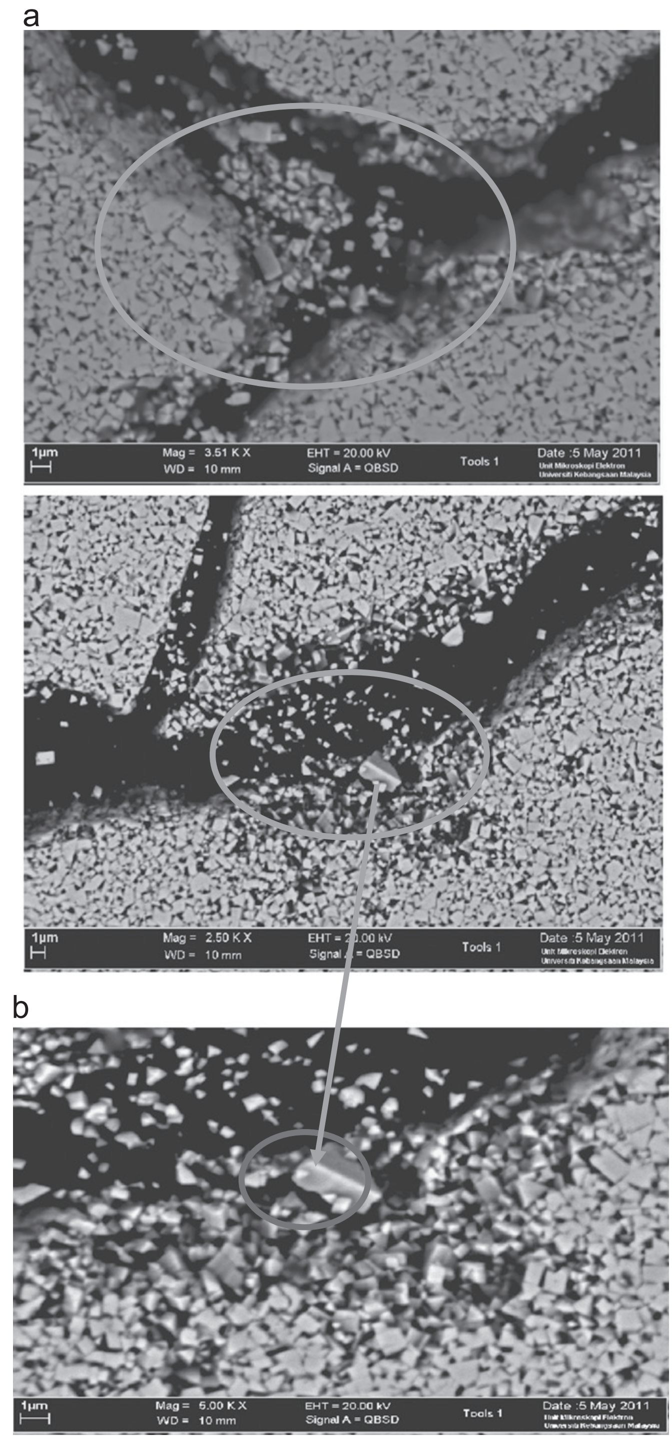

Fig. 7. Higher magnification of zone C showing the brittle fracture: (a) higher magnification of zone C and (b) loosen particle of tungsten carbide.

speeds above 150 m/min. Fig. 9 shows the cutting tool surface that experienced wear, which later led to the total fracture of the carbide cutting tool.

Fig. 10(a) and (b) show the chipping of the cutting edge that led to crack formation and brittle fracture. According to Ginting and Nouari [10], higher cutting force resulted in more wear, which accelerated crack propagation and consequently brittle fracture. The segregation of brittle chipping material may have been due to the machining parameters, cutting force and/or cutting temperature. According to Arvieu et al. [17], a high cutting temperature was generated when machining titanium alloy, which caused a chemical reaction between the coating material and titanium alloy. The results of EDX analysis are shown in Table 8(a) and (b) when machining at 135 m/min with a depth of cut of 2 mm, a feed rate of 0.1 mm/tooth and 50 mL of coolant. A high Ti content (88.36 wt%) was detected in particles adhered to the tool, as shown in

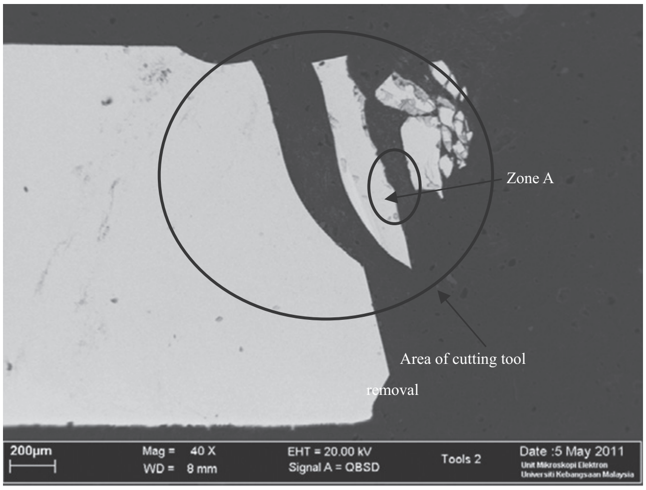

Fig. 8. Failure mode of carbide cutting tool at cutting speed of 135 m/min, MQL 50 mL, feed rate 0.1 mm/tooth, and depth of cut 2 mm.

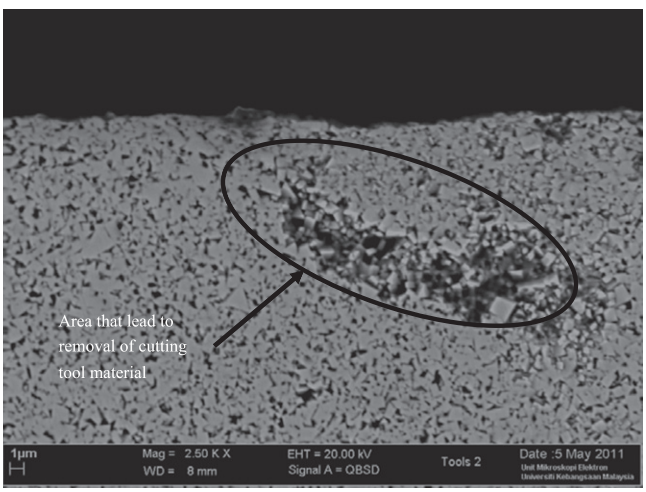

Fig.9. Higher magnification of cutting tool surface that experienced wear.

Table 8(a). On the wear surface of the cutting tool, a Ti content of 35.01 wt% was detected. It is believed that the detected Ti content is a result of the chemical reaction between the coating material and titanium alloy.

3.2. Future recommendations to improve the material properties of cutting tools

From the results discussed above, it was found that the failure mode of the carbide cutting tool was mainly due to the sudden load applied to the cutting edge, which led to cracking and brittle fracture at 120 m/min. In this study, the carbide cutting tools tested were of fine- and medium-grade hardness (maximum hardness $\sim$1000 HV_{30}) [18]. A higher level of hardness can be accessed by choosing the ultrafine carbide cutting tool grade (average hardness $\sim$2000 HV_{30}). If one were to use these recommended grades, which offer a hardness nearly equivalent to that of TiN coatings [13], the machining process can be carried out using an uncoated tool, particularly at cutting speeds of 120 m/min and below. Recent findings made by Egashira et al. [19] indicate that the average lifetime of tools made of ultrafine-grain-sized cemented tungsten carbide is improved relative to that of tools composed of coarse grains.

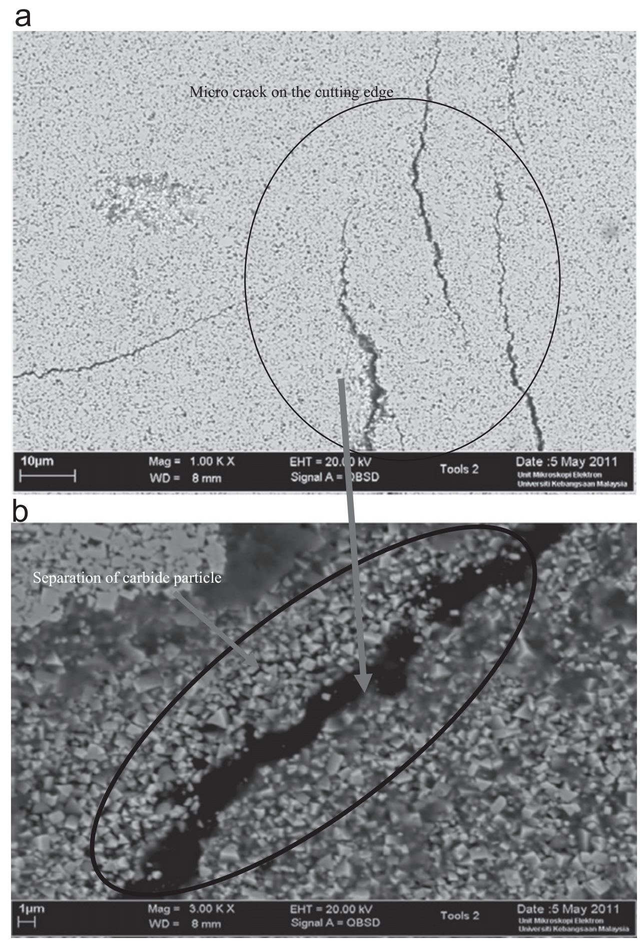

Fig. 10. (a) Microcrack on the cutting edge that is responsible for chipping in zone A and (b) high magnification of microcrack that causes brittle fracture.

Furthermore, in this study, when machining at cutting speeds above 135 m/min, failure was predominantly controlled by the wear mechanism due to the high cutting temperature that was generated, which led to crater formation. Therefore, besides being hard, the cutting tool material and coatings should be able to withstand high cutting temperatures. Garcia and Pitonak [20] found that cemented carbides sintered under de-nitriding and nitriding conditions will improve the wear performance of the inserts, particularly their wear resistance against crater formation. Furthermore, for operations dominated by interrupted cutting conditions with high loads/impacts, fcc-free, functionally graded substrates coated with the novel HT-Ti(C,N)/κ-Al_2O_3 multilayer are superior due to their stable cutting tip performance (less chipping) [20]. Recent findings made by Zheng et al. [21] suggest that the life of cemented carbide tools used to mill Ti6Al4V alloy

Table 8
EDX analysis (a) particle adhered on tool (b) on wear surface of tool when machining at 135 m/min, depth of cut 2 mm, feed rate 0.1 mm/tooth and coolant 50 mL.

Element	App conc.	Intensity corrn.	Weight (%)	Height% sigma	Atomic%
(a)					
C (K)	3.13	0.6576	4.32	0.50	14.95
Al (K)	2.40	0.6770	3.21	0.17	4.95
Ti (K)	95.78	0.9832	88.36	0.59	76.74
V (K)	4.39	0.9689	4.11	0.35	3.36
Totals	100.00				
(b)					
C (K)	5.58	0.5164	5.84	0.74	28.78
Al (K)	4.00	0.8881	2.43	0.16	5.34
Ti (K)	59.10	0.9127	35.01	0.53	43.27
V (K)	2.46	0.9355	1.42	0.26	1.66
Co (K)	8.33	0.9782	4.60	0.31	4.62
W M	8.05	0.8326	50.69	0.67	16.32
Totals	100.00				

can be enhanced by using TiSiCN- and CrSiCN-coated tools. In the future, it is suggested that researchers develop and test more novel coating materials that can prolong the lifetime of carbide tools used to machine titanium alloy.

4. Conclusion

The short lifetime of carbide tools is commonly associated with undesirable wear mechanisms and tool failure modes. The wear mechanism of chipping and the sticking of chips onto the edges of cutting materials lead to stress concentration along the cutting edge, which is in turn responsible for tool failure. In this study, carbide tools were observed to fail due to brittle facture. This failure mode was initiated by the formation of micro cracks, which then propagated until total fracture occurred. Carbide is inherently a brittle material; thus, brittle fracture was expected to occur in this study. However, catastrophic failure should be avoided to prevent long set-up times, which affects manufacturing productivity. Therefore, if this type of carbide cutting tool is to be used, it is suggested that the cutting speed be set to 120 m/min to enhance tool life and avoid catastrophic failure. Better carbide cutting tool properties are expected to be obtained by using ultrafine carbide cutting tool grades in conjunction with advanced sintering processes such as de-nitriding and nitriding and novel coatings such as HT-Ti(C,N)/κ-Al_2O_3, TiSiCN and CrSiCN. These improvements are likely to enhance tool life when cutting a given material under investigation.

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