Development of AlTiN Coated Carbide Bandsaw for Machining Titanium-17 Alloy

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ABSTRACT

Machining titanium and its alloys such as Ti-17 in an economical and efficient way has always been a challenge for the metal cutting industry due to their poor machinability characteristics. The productivity, product quality and tool life are significantly affected due to the high thermal and mechanical stresses generated at the tool workpiece interface during machining of titanium alloys. In recent years, aluminium titanium nitride coating (AlTiN) have attracted increasing attention over traditional TiN coating, mainly due to its ability of enhancing wear resistance and oxidation resistance at elevated temperature. Bandsawing of titanium alloys has not been investigated in a greater detail compared to other machining operations such as turning, milling etc. In the present investigation, AlTiN coating was deposited onto carbide tipped bandsaw teeth using cathodic arc evaporation technique and was characterized for structural, chemical and mechanical properties. A modified lathe machine was used for performing the machining tests using both the un-coated and AlTiN coated bandsaw teeth. Forces experienced by the bandsaw teeth during the machining tests were measured and specific cutting energy was calculated from the force data. The wear and failure characteristics of the bandsaw teeth were investigated using a Scanning Electron Microscope (SEM) and Energy Dispersive X-ray (EDX) spectrometer. The results showed that the AlTiN coated bandsaw teeth performed better than the un-coated bandsaw teeth in terms of wear length, force and specific cutting energy.

KEYWORDS: Carbide tipped bandsaw, Bandsawing, Ti-17 alloy, AlTiN coating, Wear, Specific cutting energy

1. INTRODUCTION

Titanium alloys are widely used in aerospace, automotive, chemical and biomedical industries, owing to their appealing and unique properties such as excellent strength to weight ratio, high strengths at elevated temperatures, fracture resistance, relatively low density and corrosion resistance (Ezugwu and Wang, 1997; Ezugwu et al., 2003; Yang and Liu, 1999; Jaffery and Mativenga, 2012). Despite the increase in the use of titanium alloys, the manufacturing industries face a significant challenge of machining these alloys in an economical way, since they are classified as difficult-to-cut materials due to some of their inherent properties (Ezugwu and Wang, 1997). Their low thermal conductivity (86% lower compared to steel) causes the machining heat to be concentrated at the tool's cutting edge. Furthermore, the ability of these alloys to maintain high strengths even at elevated temperatures leads to excessive stresses being generated on the cutting tool. These unique machining characteristics of titanium alloys generate higher cutting forces and temperatures in the cutting tools resulting in an accelerated tool wear, plastic deformation, premature failure etc. and also affect the workpiece surface finish and surface integrity (Che-Haron, 2001).

As far as the machining of titanium alloys is concerned tungsten carbide (WC) is still considered to be the best choice in order to maximise machining performance, to minimise cost related to cutting tools and to attain improved workpiece surface quality (Su et al., 2006). However, WC tools are still prone to wear (flank wear, crater wear, notching) and failure (chipping, catastrophic tool failure) even at low cutting speeds ranging from 30 m/min to 100 m/min (Kitagawa et al., 1997). Adhesion, attrition and diffusion are generally identified as the principal wear mechanisms in WC tools (Jawaid et al., 2000; Jawaid et al., 1999; Jianxin et al., 2008; Sharif and Rahim, 2007; Rahim and Sharif, 2007). It is well established that advanced hard coatings on cutting tools enhance wear resistance, minimise tool workpiece adhesion and reduce oxidation and diffusion of tool materials. Therefore, with coated carbide tools, higher cutting speed can be employed in machining of titanium alloys leading to higher productivity and lower cost.

Over the last few decades, transition metal nitride coatings, such as TiN have been successfully applied to metal cutting tools to enhance their performance and lifetime. However, in hostile cutting environments, such as machining difficult-to-cut materials, high speed machining, dry machining etc, TiN coating cannot offer the beneficial effects due to the degradation of the coating properties only at 450^{o}C. In order to enhance the properties of binary TiN coating, various alloying elements (e.g., Al, Si, Cr etc.) have been added to form ternary coatings such as AlTiN, TiSiN, TiCrN etc. Among them AlTiN has become popular in metal cutting industry due to its improved mechanical and physical properties, which leads to enhanced wear resistance and high temperature oxidation resistance (Paldey and Deevi, 2003; Paldey and Deevi, 2003; Bouzakis et al., 2012; Vetter et al., 2005; Kutschej et al., 2005; Cai et al., 2011; Chen et al., 2012). The incorporation of Al into TiN forms a metastable $Ti_{1-x}Al_xN$ solid solution, which can resist oxidation at temperatures higher than 700 ^{o}C by forming a protective Al_2O_3 layer. However, a higher amount of aluminium (greater than 65 percent) in the AlTiN coating leads to degradation of coating properties as a result of a change in the crystal structure from cubic to hexagonal (Kutschej et al., 2005, Chen et al., 2012). Several studies have confirmed the improved performance of AlTiN coatings in laboratory wear tests (Singh et al., 2005; Ding et al., 2008) and practical machining applications (e.g., turning, milling and drilling) (Horling et al., 2005; Arndt and Kacsich, 2003; Harris et al., 2001, Knutsson et al., 2011).

Although much attention has been paid on secondary machining operations (e.g., turning, milling, drilling etc.), very little or no attention has been paid on primary machining operations (e.g., bandsawing). Owing to the scientific work carried out by several researchers, bandsawing is now a well understood machining operation (Sarwar et al., 2007; Ahmed et al., 1991; Andersson et al., 2001). The characteristic features of material removal in bandsawing operation is a function of cutting edge with limited sharpness (5 μm to 15 μm) and the layer of material being removed is very small (5 μm to 50 μm). Furthermore, the chips formed during the bandsawing operation have to be accommodated in the gullet and ejected at the end of the cut. This situation can lead to inefficient metal removal operation by a combination of piling up, discontinuous chip formation and ploughing action in contrast to most of the single point cutting operations (e.g., turning). Most of the bandsawing studies were focused on machining steel workpieces by bi-metal high speed steel bandsaws. Up to now very little information is available in the public domain on the bandsawing of titanium alloys (Sarwar et al., 2010). Therefore, more scientific data are necessary to establish the machining characteristics of titanium alloys. This will assist in minimising the cost per cut when cutting titanium alloys with bandsaws. The aim of the current investigation is to evaluate the machining characteristics of Ti-17 alloy with uncoated and AlTiN coated carbide bandsaws.

2. EXPERIMENTAL PROCEDURE

2.1. Workpiece material

Beta rich alpha-beta Ti-17 alloy was considered as the workpiece material for this investigation as it is widely employed in aero engines. Relevant properties of Ti-17 alloy are shown in Table 1(30). The chemical composition of the workpiece material was measured using an Energy Dispersive X-ray Spectroscopy (EDX) and presented in Table 2.

Table 1. Mechanical properties of Ti-17 alloy [30]

Density (Kg/m^3)	**Ultimate tensile strength (MPa)**	**Yield Strength (MPa)**	**Hardness (HRc)**
4658	1172	1104	39

Table 2. Chemical composition (wt%) of Ti-17 alloy

Element	Al	Sn	Zr	Mo	Cr	Ti
Average Wt %	5.5	2.5	2.5	4.5	4.5	Bal.

2.2. Cutting tool

Tungsten carbide tipped bandsaw teeth were used for the machining tests. A picture of bandsaw tooth geometry is presented in Fig. 1. It would be interesting to note that the bandsaw teeth were honed to make small flat on the clearance side. The geometrical features of bandsaw teeth employed for the machining tests were characterised and presented in Table 3. A number of single bandsaw teeth were coated with AlTiN coating in an arc evaporation system at a deposition temperature of approximately 450 ^oC.

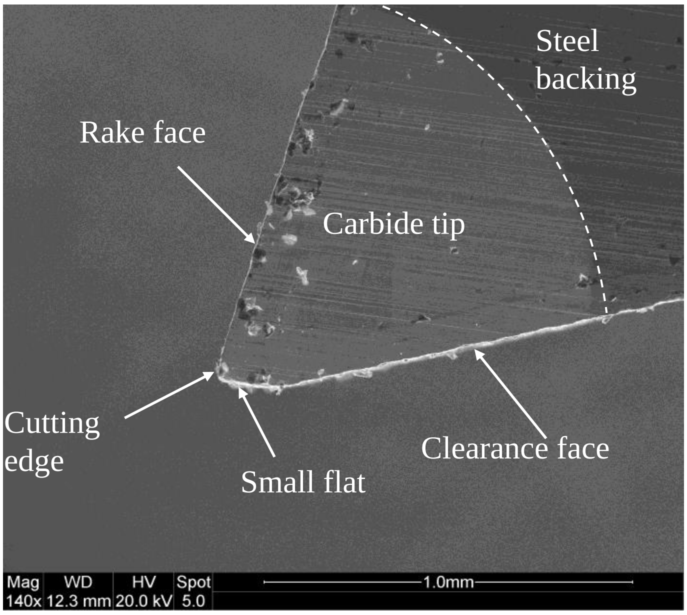


Figure 1. Bandsaw tooth geometry

2.3. Coating characterization

Coating thickness, surface morphology and fractured cross-sectional microstructure were assessed using a Scanning Electron Microscope, SEM (FEI Quanta 200 ESEM with tungsten filament). The chemical composition of the coating was analysed by the EDX (Oxford Instruments). The crystal structure of the coating was determined by glancing angle X-ray diffraction (GAXRD) technique using an angle of incidence of 2°. A Cu-Kα radiation source (wavelength of 0.15405 nm) was used at 40 kV and 40 mA. Nano indentation test on the coating was performed using a Hysitron Triboindenter fitted with a Berkovich indenter (tip radius of 100 nm). The maximum indentation depth was less than 10% of the coating thickness to avoid the effect of substrate. Adhesion of the coating was evaluated qualitatively using a Rockwell C indenter under a load of 1471 N. Scratch test was also carried out with a loading rate was 100 N/min and an indenter transverse speed of 10 mm/min.

2.4. Cutting test procedure

Full product bandsaw testing is complex, expensive and time consuming. In the current work, performance of the uncoated and AlTiN coated bandsaw teeth was evaluated using a single tooth time compression technique, which used a single bandsaw tooth instead of a complete bandsaw blade (Sarwar, 1998).A modified lathe machine was employed for machining set-up and four sections of workpieces were attached with the chuck to simulate the interrupted cutting action in bandsawing. Width of cut for all the tests was set to approximately 1 mm, which was less than the average tooth tip thickness (Table 3). In addition, a depth of cut or feed of 10 µm and a cutting speed of 40 m/min under flood cooling condition were chosen for the tests. The machining parameters are presented in Table 4.The authors have previously established that with the selected machining parameters bandsaw tool life can be maximised (Sarwar et al., 2010). Typical chips formed during the bandsawing of Ti-17 alloy are shown in Fig. 2. Cutting forces were measured during the tests using a Kistler dynamometer and associated electronic equipments. The wear modes, wear mechanisms and wear length in the bandsaw teeth were investigated under the SEM.

Table 3. Characteristics of a carbide tipped bandsaw.

Bandsaw tooth characteristics	**Description**
Tooth pitch	1.4/2 TPI
Microstructure of carbide tip	Tungsten carbide with cobalt binder

Microstructure of steel backing material	Tempered martensite
Average thickness of cutting edge	1.61 mm
Length of a single bandsaw tooth	54 mm
Width of a single bandsaw tooth	20 mm
Average rake angle	9.8°
Average clearance angle	20.1°
Average set magnitude	0.58 mm
Average cutting edge radius	13 μm
Average honed length	130 μm

Table 4.Operating conditions for the cutting tests

Cutting speed (m/min)	Feed (microns)	Width of cut (mm)
40	10	1

Figure 2. Optical image showing the chips formed during bandsawing of Ti-17 alloy (×10)

3. RESULTS AND DISCUSSIONS

3.1. Coating characteristics

EDX analysis showed that atomic percentage of the elements in AlTiN coating was very close to stoichiometric value (Fig. 3). The atomic percentage of Al (62.13 at %) was higher than that of Ti (38.84 at %). AlTiN coating possesses better properties than aluminium-free TiN coating and the higher is the ratio of aluminium to titanium in the coating, the better are the properties. Furthermore, the AlTiN coating with high aluminium content (up to 65 to 67 at%) have shown improved tool life in machining applications (Horling et al., 2005; Arndt and Kacsich, 2003).

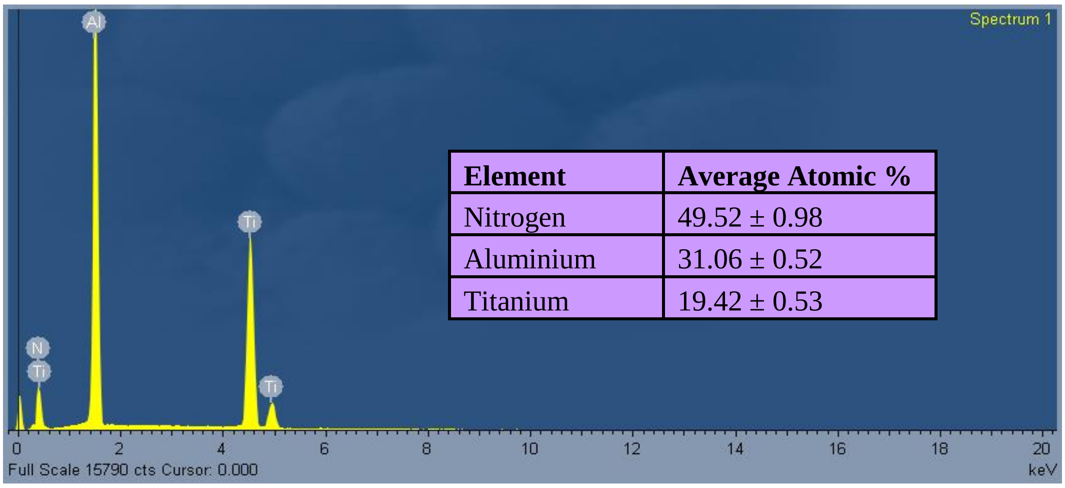


Figure 3. Spectra of elemental composition in AlTiN coating obtained by EDX

The XRD pattern of AlTiN coating shown in Fig.4 revealed that the coating exhibited face centred cubic (FCC) structure with multiple orientations of (111), (200), (220) etc. and the preferred orientation being in the (111) direction. The narrow peak widths in the spectra indicated that the coating was highly crystalline. Although it was reported in the literature that the increase in aluminium content in AlTiN coating promoted the formation of (200) texture (Kutschej et al., 2005; Cai et al., 2011), it was not observed in the current study. However, a (111) preferred orientation has been noticed in a cathodic arc deposited AlTiN coating with high aluminium content (63 at%) (Chang and Wang, 2007).An aluminium content greater than 70% promotes the formation of a mixed cubic (NaCl) and wurtzite (ZnS) structures, which has a detrimental effect on the mechanical properties of AlTiN coatings (Chen et al., 2012). No signals from wurtzite crystals indicated that the percentage of aluminium in the coating was less than 70%, which was in agreement with the findings in EDX analysis. Therefore, the coating preserved TiN crystal structure with a slight decrease in the lattice parameters. The diffractogram also showed a number of peaks from the tungsten carbide substrate. The average grain size of the crystallites in the coating was calculated to be approximately 34.3 nm, which was in agreement with the work reported in literature on AlTiN coatings deposited by cathodic arc evaporation method (Chang and Wang, 2007).

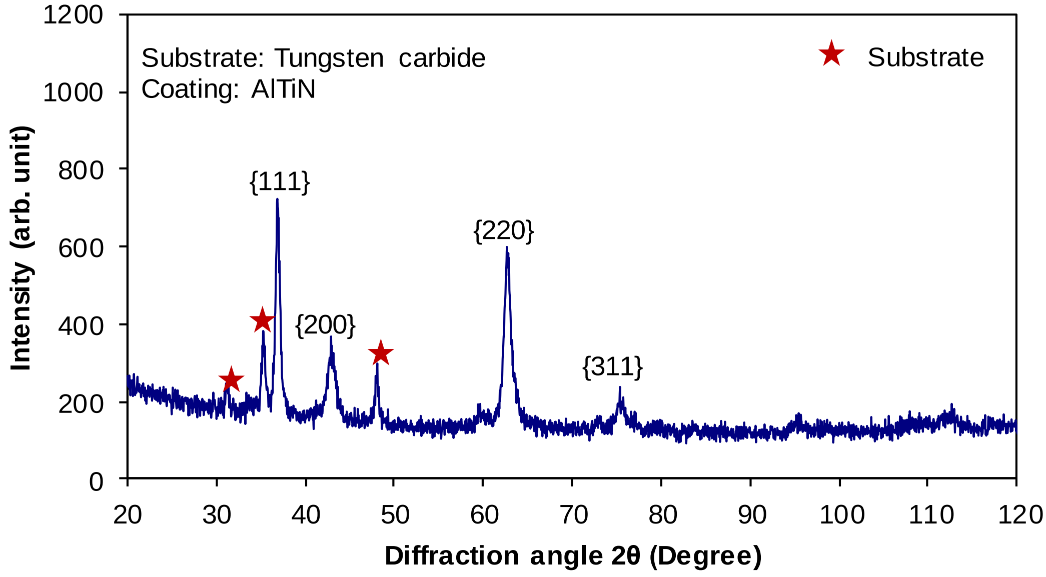


Figure4. X-ray diffraction pattern of AlTiN coating

The surface morphology of the coating exhibited micro-pores and droplets, which were characteristics of cathodic arc evaporation process (Fig. 5a). The average size of the micro-pores was between 1-3 µm, whereas the micro-particles were in the range of 2-5 µm. However, the micro-particles can amalgamate and the overall size could increase up to 10 µm. The cross sectional microstructure demonstrated that the coating was deposited as a single layer with a dense and columnar structure (Fig. 5b). Similar microstructures were also reported in the literature for AlTiN coating deposited by cathodic arc evaporation technique (Arndt and Kacsich, 2003). The thickness of the AlTiN coating was calculated to be approximately 2.4µm, using image analysis software attached to the SEM.

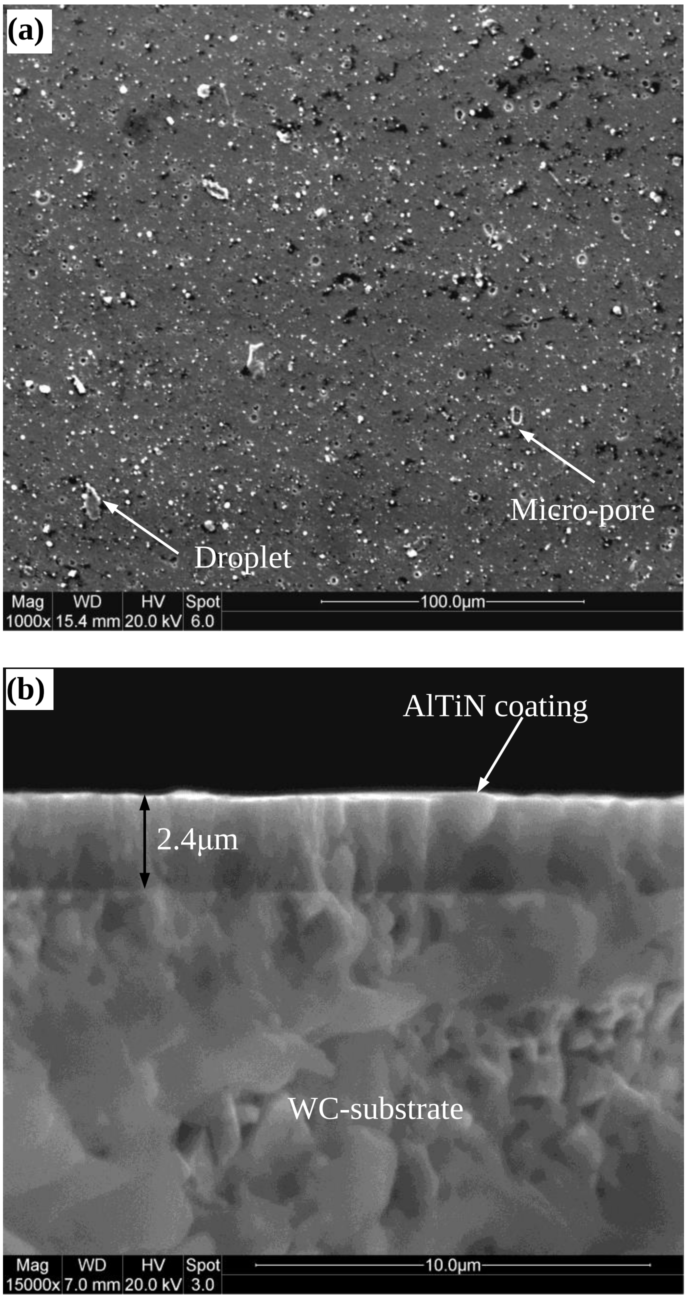


Figure5. SEM images of AlTiN coating: (a) surface morphology and (b) fractured cross-sectional microstructure

The hardness and Young's modulus of the AlTiN coating were found by the data related to applied force versus indentation depth from the nano indentation tests using Oliver and Pharr method[Oliver and Pharr, 1992; Oliver and Pharr] and were found to be 32.0 ± 9 GPa and 372.08 ± 68.7 GPa respectively. Generally the hardness of AlTiN coatings deposited byc athodic arc evaporation technique varies between 28 GPa and 34 GPa (Paldey and Deevi, 2003; Horling et al., 2005; Sato et al., 2003). The hardness strongly depends on the composition of the AlTiN coatings, particularly on aluminium content. Chen et al. reported that an increase in aluminium content for the single phase cubic coatings increased hardness from ~22.8 GPa for TiN to 31.9 GPa for $Ti_{0.48}Al_{0.52}N$ and 31.3 GPa for $Ti_{0.38}Al_{0.62}N$ due to changed binding characteristics (Chen et al., 2012). A further increase in aluminium content resulted in decreases the hardness mainly due to the transformation from cubic structure to wurtzite structure. The high hardness in AlTiN coating compared to TiN is generally attributed to the solid solution formation through the dissolution of Al atoms in the TiN crystallite.

The study of Rockwell C indentation on the coating revealed very small cracks with no delamination of the coating around the indentation (Fig. 6a). This indicated that the coating was tough and well adhered with the substrate (HF1 OR HF2). The higher critical load (~ 75 N) for coating failure found in the scratch test also supported the finding in Rockwell C test. Again, no evidence of brittle fracture around the scratch track ascertained the good toughness of the coating (Fig. 6b).

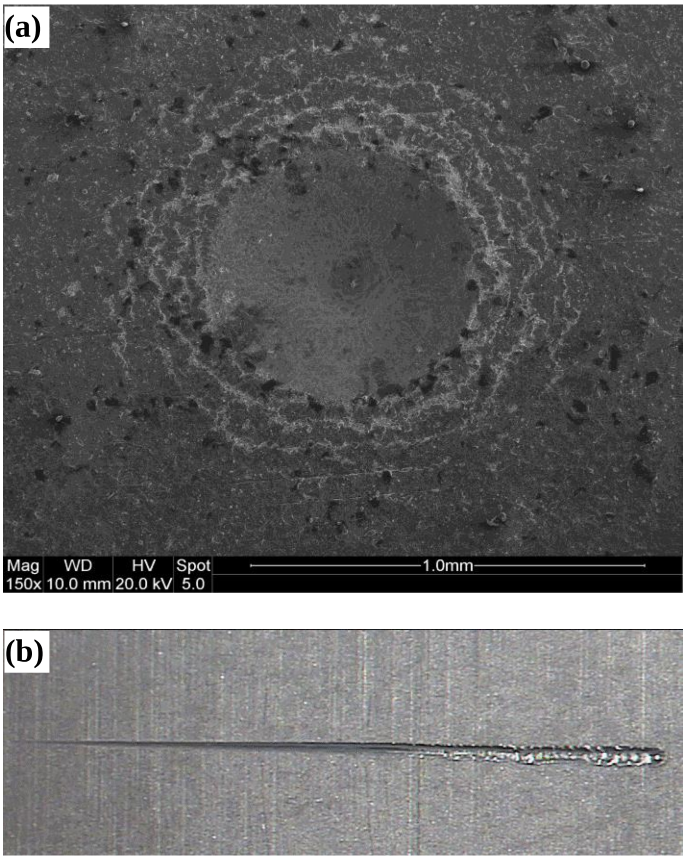
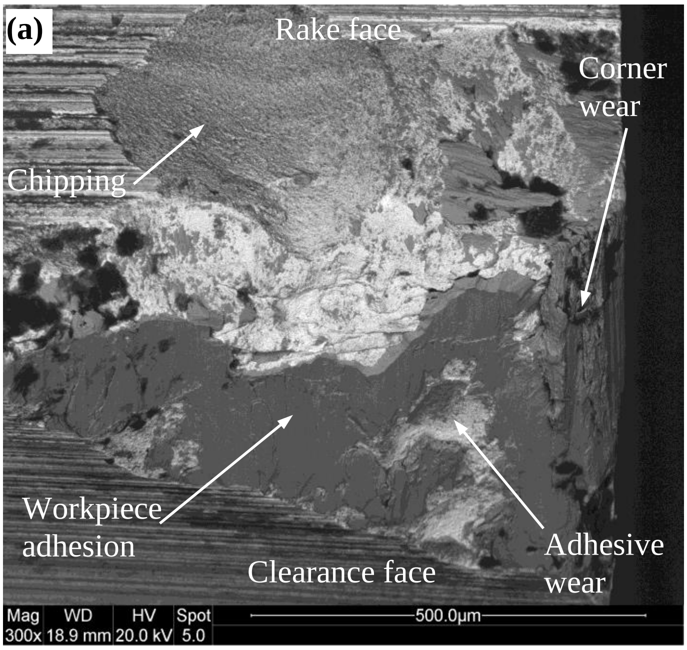


Figure 6. Micrographs of (a) Rockwell C indentation and (b) scratch track generated in AlTiN coating

3.2. Wear and failure modes in bandsaw teeth

In order to determine the wear and failure modes and to compare the condition of the uncoated and AlTiN coated bandsaw teeth, the machining test was periodically interrupted and finally stopped after cutting 5,700 m. Fig. 7 shows magnified corners of the bandsaw cutting edges. Corner wear and flank wear were identified as the principal wear modes in bandsaw teeth. The maximum wear appeared at the corner of the cutting edge that was engaged with the workpiece and gradually decreased across the thickness of the cutting edge. This could be due to the engagement of the cutting edge at an angle with the workpiece as a consequence of the set geometry (Set and twist angles) of the bandsaw tooth. Furthermore, the width of cut (1 mm) was smaller than the thickness of the cutting edge (1.6 mm).



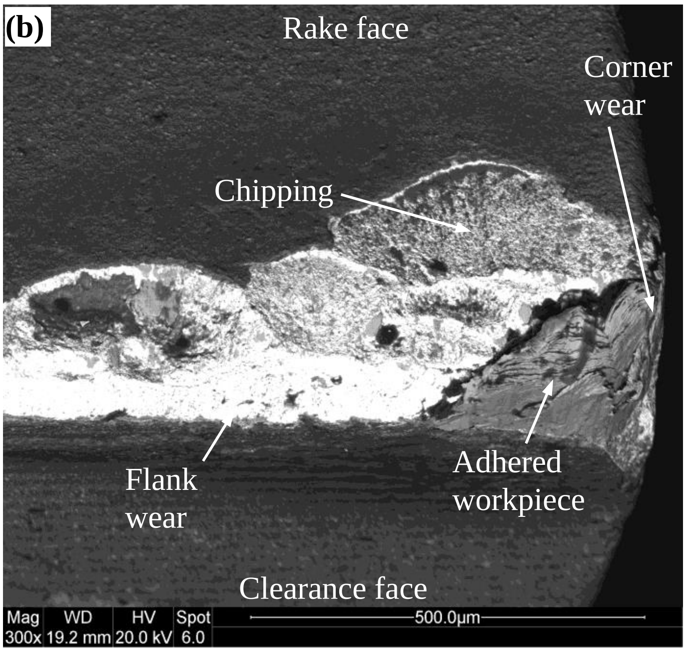


Figure 7. Magnified images of the corner of bandsaw teeth after 38,000 cuts: (a) uncoated edge and (b) AlTiN coated edge

Higher load at the corner would generate higher stress and temperature. This could reduce the yield strength of the tool material and resulted in an accelerated wear at the corner (Che-Haron, 2011). It was evident that the cutting edge in the uncoated tooth was completely damaged with non-uniform wear extending in both rake and clearance faces along with severe corner wear. On the other hand, the cutting edge of the AlTiN coated tooth suffered less wear at the corner and flank face. However, chipping on the rake face was evident in the coated tooth. The corner wear length in the uncoated tooth at the end of the machining tests was almost twice the wear length in the coated tooth (Fig. 8). This means that the tool life was increased by approximately 45% with the incorporation of AlTiN coating on the bandsaw.

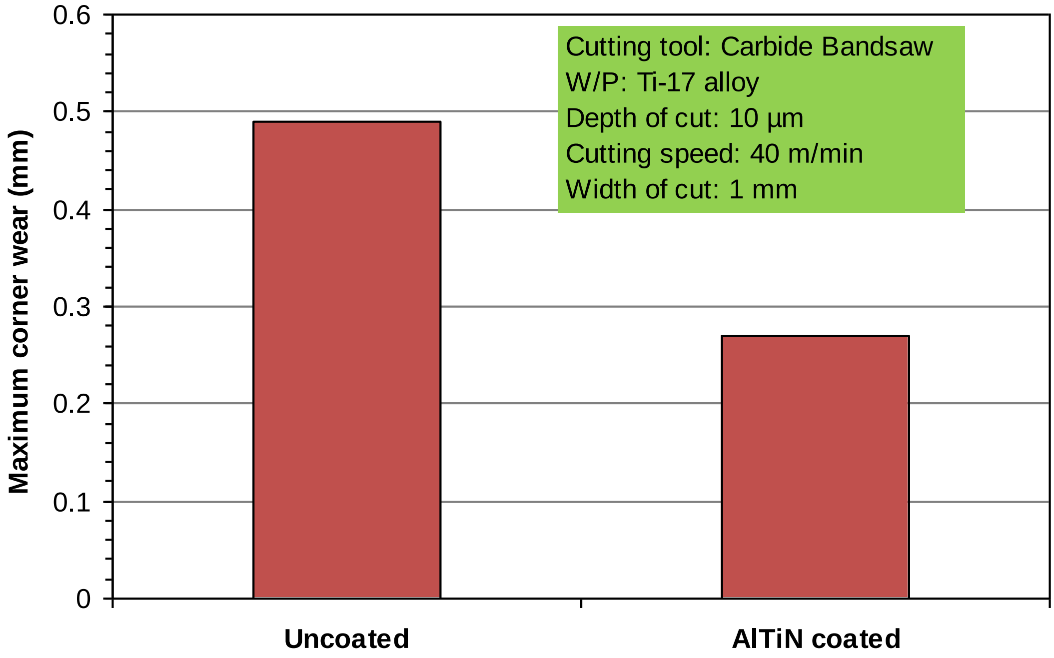


Figure8. The comparison of durability between the uncoated and AlTiN coated bandsaw teeth in terms of corner wear

Chipping on the rake face was observed as the main failure mode in both the uncoated and AlTiN coated teeth. However, the extent of chipping was much higher in the uncoated tooth causing a catastrophic failure of the tooth. Cyclic mechanical and thermal loadings due to the periodic engagement and disengagement of the tooth with workpiece during machining are generally attributed for the cause of chipping (Che-Haron, 2011; Jawaid et al., 1999; Sharif and Rahim, 2007; Rahim and Sharif, 2007). The brittle characteristic of the carbide material could also be a contributing factor for chipping in the interrupted machining test.

Another failure mode in the form of microcrack was also observed in the bandsaw cutting edge as shown in Fig. 9. The interrupted cutting condition and the generation of high temperature during the bandsawing test could be responsible for the generation of cracks. After the generation of initial cracks, they could further extend into the carbide tip with prolonged machining and finally lead to chipping of the edge. However, it must be stated that chipping could take place without the formation of cracks (Rahim and Sharif, 2007).

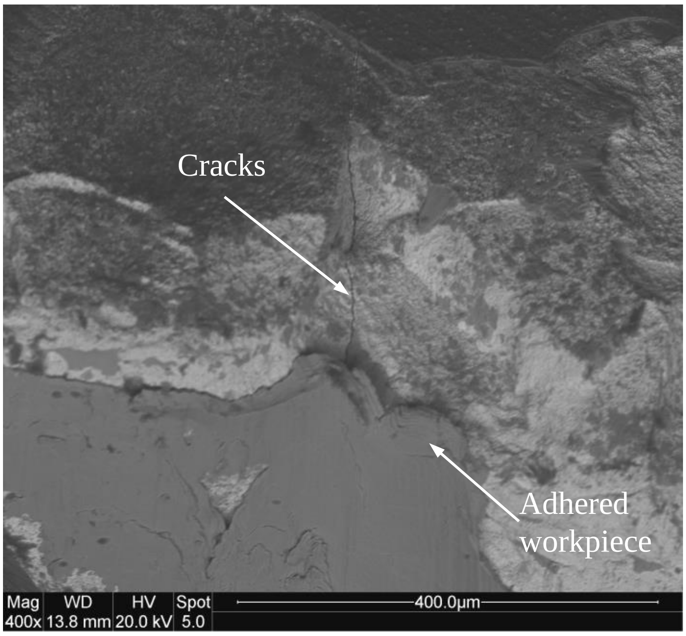


Figure9. Bandsaw cutting edge showing cracks

Therefore, it can be concluded that wear and failure in the bandsaw teeth were caused owing to the high stress and temperature generated during machining titanium alloy. AlTiN coating improved the wear resistance of the bandsaw tooth and contributed to the enhancement of the tool life.

3.3. Wear mechanisms in bandsaw teeth

The SEM images in Fig. 7 exhibited a clear evidence of the workpiece material adhering to the uncoated cutting edge. The high temperature and stress generated during machining caused the welding of the workpiece material to the cutting edge. The process also led to the modification of the cutting edge (Armendia, et al., 2010). The amount of adhering workpiece material could affect the cutting force. When the adhered workpiece layer attained a critical size, it was detached from the cutting edge along with tool material and was removed with the flowing chip. This process would increase the wear and also encourage the chipping of the bandsaw cutting edge.

Attrition was also identified as another dominant wear mechanism in the uncoated bandsaw cutting edge. Attrition is defined as the process of removing particles or grains of tool material by adherent chip or workpiece (Jawad and Sharif, 2000; Rahim and Sharif, 2007). The uneven wear on the worn cutting edge evidenced that fragments of the tool had been plucked away by the adhering workpiece material or flowing chip (Fig. 10). The attrition wear process caused a gradual increase of wear in the cutting edges.

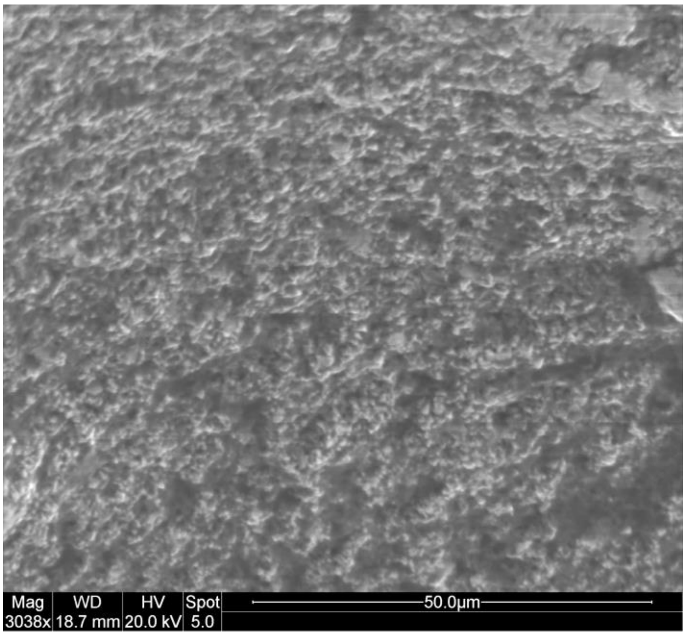


Figure 10. SEM picture of bandsaw cutting edge showing attrition wear

Apart from adhesion and attrition, diffusion wear was identified by the elemental analysis of the workpiece material adhered to the worn tool. The SEM images of the analysed area and the corresponding EDX spectrum are shown in Fig. 11. The presence of carbon and cobalt in the adhered material indirectly indicated that diffusion of the elements from the carbide tool into the workpiece material took place at the tool-chip interface, therefore confirming the diffusive wear. The high stress and temperature at the tool workpiece contact point created a favourable environment for the diffusion of tool elements. Similar results were also observed by other researchers when machining titanium alloy with carbide tool (Su et al., 2006; Jawaid et al., 2000; Arrazola et al., 2009). Diffusion in tungsten carbide can start at a temperature as low as 400 ^{o}C (Jianxin et al., 2008). Even under moderate cutting conditions the temperature at the tool edge could exceed much higher than 400 ^{o}C when machining titanium alloy with carbide tools. In the event of diffusion, a deficiency of carbon and cobalt in the carbide tool resulted in a weakened tooth, which accelerated the wear. However, no sign of diffusion of heavier element (tungsten) was evidenced in the EDX spectra. This could be an indication of mild diffusion process as moderate cutting speed and low feed per tooth were employed in the bandsawing tests.

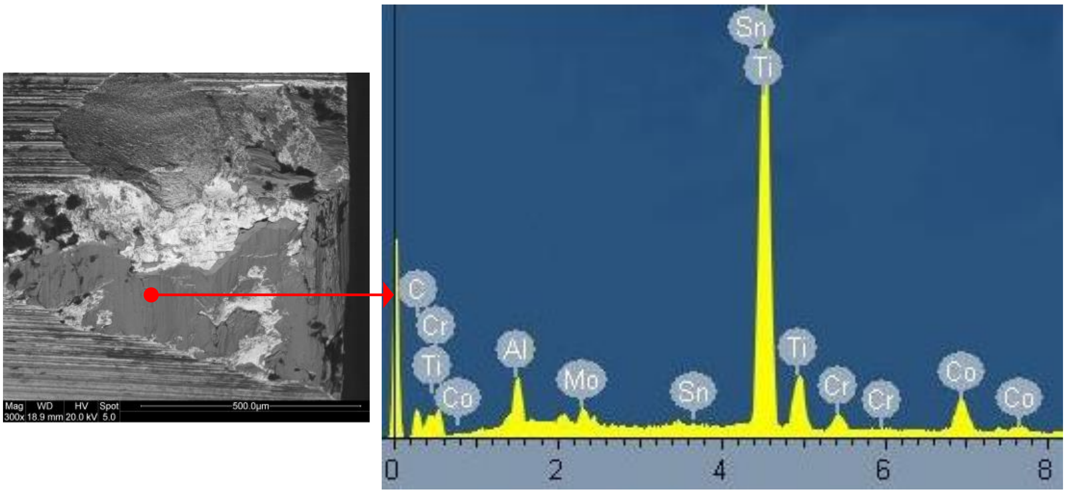


Figure 11. EDX spectra of adhering workpiece on the bandsaw cutting edge showing elemental diffusion

In contrast to the uncoated bandsaw tooth, gradual removal of coating mainly from the flank face was identified as the initial wear mechanism in the AlTiNcoated bandsaw tooth. This could be due to the interaction between the coating and the machined workpiece. Although chipping was observed at the rake face of the coated tooth, there was evidence of substrate exposure through gradual wear of the coating. Subsequently the exposed substrate was subjected to adhesion, attrition and diffusion wear. However, the remaining coating on the rake and flank face acted as a barrier to slow down the progression of further wear. The quantity of adhering workpiece material was found to be lower on the AlTiN coated tooth (Fig. 7), compared to the uncoated coated tooth possibly due to the high heat resistant, chemical resistant and lower fiction characteristics of the coating. Hence, the coating provided continuous resistance against wear leading to much more predictable tool life, reduced risk of unexpected failure and extended tool life. Very little or no attrition was found in the coated cutting edge. It should, however, be noted that once AlTiN coating was removed from the bandsaw cutting edge during machining, subsequent wear mechanisms in the coated teeth were exactly same as in the un-coated bandsaw.

3.4. Specific cutting Energy

Specific cutting energy (E_{sp}) parameter is a measure of the energy required to remove a unit volume of workpiece material and it reflects the efficiency of the cutting process. Moreover, E_{sp} can be used to correlate various stages of tool wear to the performance of the bandsaw teeth, as it is more sensitive to low depths of cut, which is the case in bandsawing operation (Sarwar et al., 2009). Fig. 12 shows the variation of E_{sp} with the length of cut produced. E_{sp} was calculated with the data associated with cutting force and material removal rate. For both uncoated and coated bandsaw teeth, E_{sp} values increased with the length of cut due to the progressive wear in the cutting edges. Owing to the tool wear and degradation, the cutting edge was modified (i.e., blunting, higher edge radius), which increased the cutting force and hence, higher E_{sp}(Sarwar et al., 2007). Moreover, the contact length between the clearance face and machined workpiece increased due to the flank wear. This resulted in increased friction and hence, higher cutting force/E_{sp}.

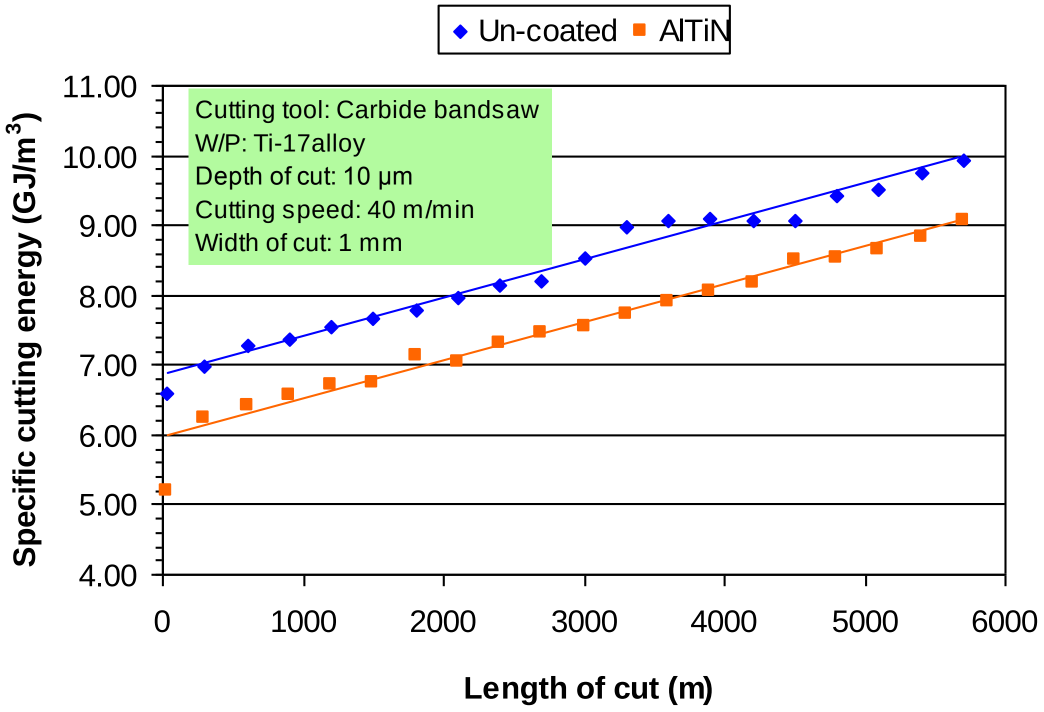


Figure 12. Comparison of Specific Cutting Energy (Esp) with the length of cut for the un-coated and AlTiN coated bandsaw teeth

At the new condition of the uncoated tooth, the E_{sp} value was measured as 6.2 GJ/m^3 and reached the maximum value of 10 GJ/m^3 at the end of the machining test. However, the E_{sp} values for the coated tooth always remained less than that for the uncoated tooth. This could be explained by the fact that the coating resisted wear and degradation of the cutting edges due to its high hardness, high oxidation resistance and low coefficient of friction.

It was also interesting to note that a small cyclic trend was observed in the E_{sp} values with the length of cut. This could be owing to the periodic adherence and removal of workpiece material on the flank face. The modification of the cutting edge due to the adhering workpiece material caused the force/E_{sp} to increase (Armendia et al., 2010). However, the E_{sp} decreased again once the original tooth geometry was restored through the removal of adhering workpiece material during machining.

4. CONCLUSIONS

The following conclusions can be drawn after carrying out comprehensive cutting tests with uncoated and AlTiN coated bandsaws on Ti-17 alloy:

(1) AlTiN coated bandsaws were produced by cathodic arc evaporation technique having coating characteristics of columnar microstructure, high hardness and good adhesion to the bandsaw teeth.

(2) Corner wear and chipping were identified as principal wear and failure modes, which controlled the life of carbide tipped bandsaw teeth.

(3) The dominant wear mechanisms were adhesion and attrition at the bandsaw cutting edge. Diffusion wear mechanism was also identified by EDX analysis.

(4) The coated bandsaw tooth performed better than the uncoated tooth as it maintained the structural integrity of the cutting edge unlike the rapid degradation in the uncoated cutting edge.

(5) The low values of specific cutting energy suggests better machinibility characteristics when using AlTiN coated bandsaw teeth to machine Ti-17 alloy.

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