

Comparative study between wear of uncoated and TiAlN coated carbide tools in milling of Ti6Al4V

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Abstract:

As is recognised widely, tool wear is a major problem in machining of difficult-to-cut titanium alloys. Therefore, it is of significant interest and importance to understand and determine quantitatively and qualitatively tool wear evolution and the underlying wear mechanisms. The main aim of this paper is to investigate and analyse wear, wear mechanisms along with surface and chip generation of uncoated and TiAlN coated carbide tools in a dry milling of Ti6Al4V alloys. Quantitative flank wear and roughness were measured and recorded. Optical and SEM observations of tool cutting edge, machined surface and chips were conducted. Results show that the TiAlN coated tool exhibits approximately 44% longer tool life than the uncoated tool at a cutting distance of 16 m. A more regular progressive abrasion between the flank face of tool and workpiece is found to be the underlying wear mechanism. The TiAlN coated tool generates smooth machined surface with a 31% lower roughness than the uncoated tool. As is expected, both tools generate the serrated chips; however, burnt chips with blue colour are noticed for the uncoated tool as the cutting continues further. The results are shown to be consistent with observation of other researchers, and further imply that the coated tools with appropriate combination of cutting parameters would be able to increase the tool life in cutting of titanium alloys.

Keywords: Tool wear, titanium alloys, tungsten carbide tools, wear mechanisms, high speed machining

1. Introduction

Due to their excellent strength to weight ratio, toughness at high temperature, corrosion resistance, titanium alloys (e.g. Ti6Al4V) have attracted tremendous attentions and been extensively applied as structural components in aerospace and biomedical industries, e.g. [1], [2]. Machining as a mechanical processing technique has been one of the fast, effective operations in manufacturing to provide the final shape of such components with required geometric accuracy and finish. However, the key challenge is the difficulty to cut or shape titanium alloy materials due to their very low thermal conductivity, e.g. [3]. As a result, the high temperature is generated at the cutting zone, thus affecting the cutting tool life (i.e. wear performance) and surface integrity of the final product. In the past, different types of cutting tool materials along with combination of various cutting parameters and environments have been investigated in cutting of titanium alloys. Cutting tools studied were made of carbide, HSS, diamond, while cutting speed and feed rate have been the dominating parameters influencing the machinability of titanium alloys [4], [5]. A common coconscious in evaluating the machinability is that the cutting tool wear is the major factor, which is a resultant of the underlying interaction and mechanics between the tool and the workpiece, impacting the manufacturing productivity. Among many tools, tungsten carbide has been a good choice and widely used cutting tool in the machining industries due to its high strength and wear resistance, e.g. [6]. The carbide tools are made of tungsten carbide (WC) with cobalt (Co) binders via compacting and sintering, making the material hard and resilient to heat and wear [7]. Often the degree of composition of WC-Co is varied to produce the tool with required mechanical and tribological properties. While diamond tools (e.g. PCD) offer relatively improved machining performance in terms of tool life, they are quite expensive and may not be affordable for mass manufacturing [8], [9]. As a result, tungsten carbide has shown tremendous potential in high speed cutting of titanium alloys. Ove the years, carbide tools have been studied in cutting of titanium alloys with a focus on understanding of wear and the associated wear mechanisms, e.g. [10], [11]. In cutting of non-ferrous metals, abrasion, adhesion, attrition and diffusion are shown to be the typical wear mechanisms, in which, adhesions and diffusions are often iterated as the dominating, particularly, when machining of titanium. Ghani et al. [12] studied the effect of various high cutting speeds (120-135 m/min) on carbide tool wear in cutting of titanium and reported that higher speed causes brittle fracture and cracking of tool edge due to high temperature induced stress concentration and intermitted fast thermal loading. They recommended suitable conservative cutting parameters to minimize tool wear effects. Hartung et al. [13] showed that crater wear due to adhesive

1 layers on the rake face is more dominant at lower cutting speeds (61-122 m/min), while the
2 tool fails due to plastic deformation at high cutting speeds (122-610 m/min). Adhesive layers
3 are the result of chemical between titanium and carbide particles via diffusion, which
4 essentially decrease the toughness of tool edge. Generally different tool materials behave
5 differently to different wear mechanisms. In this regard, hard and wear resistant coatings, e.g.
6 TiN, TiCN, are applied on the tool edge to improve the performance. Surprisingly, **Ezugwu**
7 **and Wang** [14] found that the uncoated tool outperforms the coated tool in cutting of titanium.
8 This is however bit contradictory to the findings of other researchers, e.g. [15]. Wear due to
9 elemental diffusion-dissolution through tool-chip of carbide tools at high cutting speeds was
10 further emphasized in [16]. In a dry cutting of titanium alloy, **Gerez et al.** [17] observed that
11 adhesive layer or built up edge generated at low cutting speeds often act as a lubricant,
12 minimizing abrasion; however, the layers are momentarily removed at high cutting speeds,
13 hence accelerating abrasion at the tool-rake interface.
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16 Therefore, it is clear that insightful understanding of wear development and mechanisms are
17 therefore becoming more important to determine the limit of the tool capability, enabling one
18 to predict the onset of generation of degraded surface due to a worn-out/failed cutting edge of
19 the tool. This also allows one to design and develop better cutting tool materials. The notion
20 of importance of the effect of tool wear on the machinability is stressed out by a wider
21 community of machining researchers, e.g. [4], [18].
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23 Keeping this spirit in mind, this paper focuses on further investigation and analysis of wear
24 and wear mechanisms of uncoated and TiAlN coated tungsten carbide tools in cutting of
25 Ti6Al4V alloys in dry conditions. To follow up and measure consistent wear development, a
26 series side milling operations with the same cutting parameters were performed. Cutting edge
27 wear, surface roughness and chips were observed and measured at a certain interval of cutting
28 distance (often noted as cutting time). Results were discussed and analysed with respect to
29 the findings available in literature.
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32 **2. Experimental details**

33 **2.1 Workpieces**

34 The machining was conducted on the workpieces made of Ti-6Al-4V alloys. The chemical
35 compositions and mechanical properties of the material are presented in Tables 1 and 2. As-
36 received material block was cut into a size of 100 (*L*) x 100 (*W*) x 80 (*H*) mm. The top and
37 bottom surfaces of the specimen were further rough machined with very small depth of cut to
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clean and even out the surfaces. This process used a 60 mm diameter solid carbide indexed cutter running with a feed rate of 500 mm/min and spindle speed of 1200 rpm.

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

Element	Ti	Al	V	Fe	C	N	H	O
Wt (%)	Balance	6.15	4.40	0.09	0.05	0.01	0.005	-

Table 2 Mechanical properties of Ti-6Al-4V alloy at room temperature of 25°C

Hardness (HRC)	Elastic modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Density (kg/m ³)
36	114	830	993	4540

2.2 Cutting tools

As cutters, two types of tungsten carbide end mills are used. One is uncoated (Hanita D014 supplied by Wahida Inc. Japan) and the other coated with TiAlN by physical vapour deposition method (KCPM 15 supplied by Kennametal Inc. USA). The geometric dimension of both cutters is as follow: diameter $D_1 = 12$ mm, no of flutes = 4, total length, $L = 83$ mm, working length, $l = 26$ mm, helix angle = 30° , axial rake angle = 6° and secondary clearance angle = 15° . Figure 1 shows photographs of both coated and uncoated carbide cutters used. The physical and mechanical properties of the tungsten carbide and TiAlN coated tools are summarized in Tables 3 and 4. Before actual cutting tests, the edges of the cutters are observed to be sharp and clean without any dirt and contaminants.

Table 3 Physical and mechanical properties of tungsten carbide end mill

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

Table 4 Physical properties of the TiAlN coating

Type	Material	Thickness	Melting point	Hardness at 25°C
PVD (physical vapour deposition)	TiAlN	4 μm	3070°C	2300 HV ₁₀

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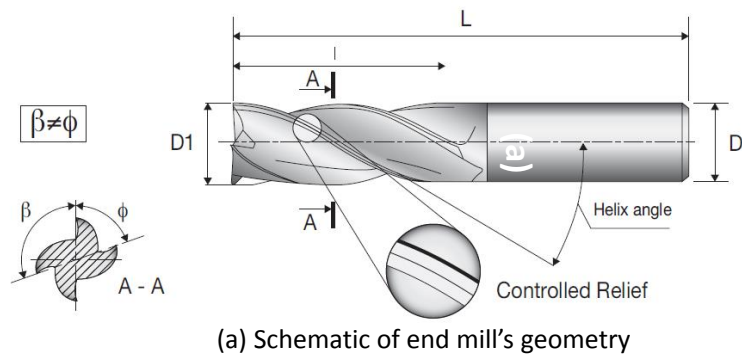


Fig. 1 Tungsten carbide end mills used in the tests

2.3 Experimental

Using a CNC 4-axis vertical milling machine (Bridgeport's VMC 480PS, USA), a series of side milling operations were performed on the workpiece. Figure 2 depicts experimental setup and illustration of cutting paths considered during tests. As titanium alloy is hard and difficult to machine material, higher cutting speed and feed rate are considered. The cutting parameters used are as follows: cutting speed $v = 80$ m/min, feed rate $f = 0.2$ mm/rev, width of cut $d = 1$ mm. During machining, the cutter is engaged with the workpiece at 10 mm deep along the tool axis direction (i.e. axial depth = 10mm; see Fig. 2). The cutting conditions were kept constant for machining with both types of cutters. In order to understand tool wear performance, the cutter was observed at a certain interval of cutting length. To do this, the cutter was taken out of the spindle head and the tool holder, and examined under the microscopes. An interval of cutting length of 1 m was considered for the uncoated cutter while a cutting length of 2 m for the coated cutter, as it is expected that the coated one will experience less wear as the cutting progress. Flank wear and wear mechanism were observed,

measured and recorded by an optical microscope equipped with high resolution camera (Wild Heedbrugg's Wild M20, V=1.4X, Switzerland). Cutting chips were collected to understand and observe the effect of tool wear on the change of temperature in cutting zone. Topology of tool, machined surface and chips were further observed by scanning electron microscopes (SEM) (FEI's Quanta 450 equipped with EDX capability, Netherland) for a closer look as well as detailed analysis. The process was kept repeated until the cutters reach closer to failure (i.e. average $VB = 0.3$ mm) according to the failure criterion [19]. All the machining was performed in dry environment without using any external coolant and lubricant. In addition to wear, roughness average of the machined surface was measured by a roughness tester (Mitutoyo's Surftest SJ-210, cut-off length =2.5 mm, contact mode, stylus tip radius=5 μ m, complies JIS-B0601 standard, Japan). Roughness on five points of the surface was measured and their average was considered the final reading. The same experimental procedure was followed for cutting tests with both uncoated and TiAlN coated tungsten carbide cutters.

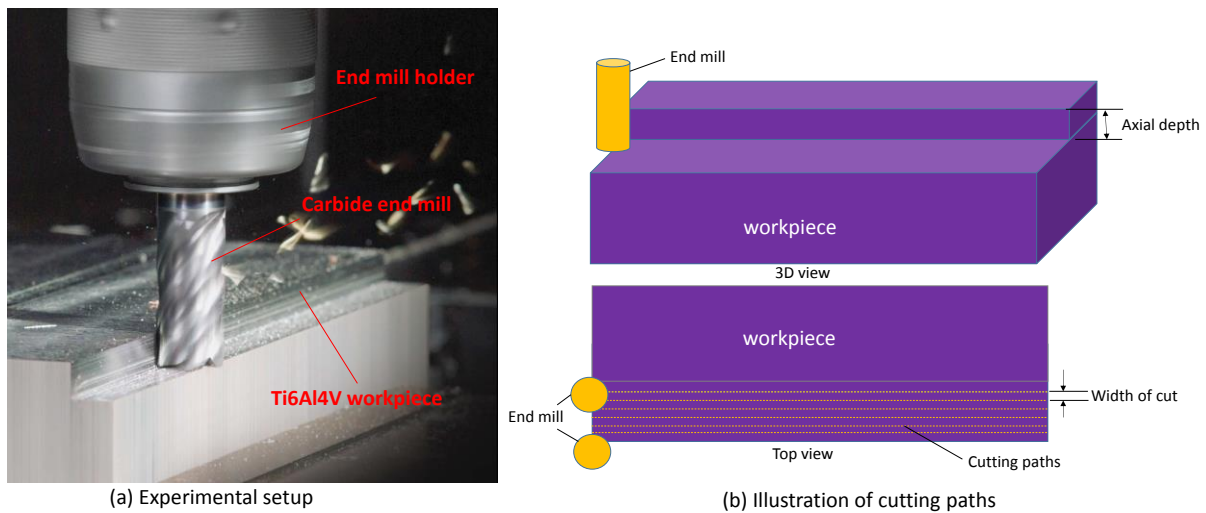


Fig. 2 Experimental setup and cutting paths used in milling tests

3. Results and discussion

3.1 Tool wear

The main focus is to investigate tool wear and wear mechanism associated when machining of titanium alloy. In general, cutting tests continue until the tool reaches a standard failure criterion (i.e. average flank wear = 0.3 mm for carbide tool). Figure 3 depicts a comparison of tool flank wear progression with respect to the cutting length for uncoated and coated tools. It can be seen from Fig. 3 that, as the cutting length increases, TiAlN coated carbide tool

exhibits a lower wear than the uncoated tool. For instance, after cutting of about 10 m, the coated tool reaches wear value of 0.1436 mm, which is about 32% smaller than that of uncoated tool (wear = 0.21 mm). The coated tool can cut up to 22 m in length with wear progression of about 0.23 mm, while the uncoated tool reaches wear of about 0.321 mm (i.e. failure criterion) at a shorter cutting distance of 16 m. In other words, overall the coated tool, after cutting of 16 m, shows an enhancement of tool life by about 44% over its counterpart. Further, generally a cutting tool follows a three region wear characteristics – (1) initial wear zone with relatively high wear, (2) steady state wear region and (3) accelerated wear region leading to failure [20]. As shown in Fig. 3, both uncoated and coated tools show approximately three wear zones as indicated by **A-B-C** and **A'-B'-C'** areas, respectively. Initial wear rate of the uncoated tool is larger than that of the coated tool as the slope of curve in 'A' zone is shown to be relatively high. Further, the steady state wear region for the uncoated tool starts after about cutting distance of 3.5 m, while for the coated tool it starts after cutting of 2 m and the stability of the region is longer as compared to that of the uncoated one. This indicates that the TiAlN coated tool exhibits a better tool life or wear resistance and can be safely used for more cutting length in machining of titanium alloys. Moreover, the findings are quite consistent with those of other researchers, e.g. [21], [22].

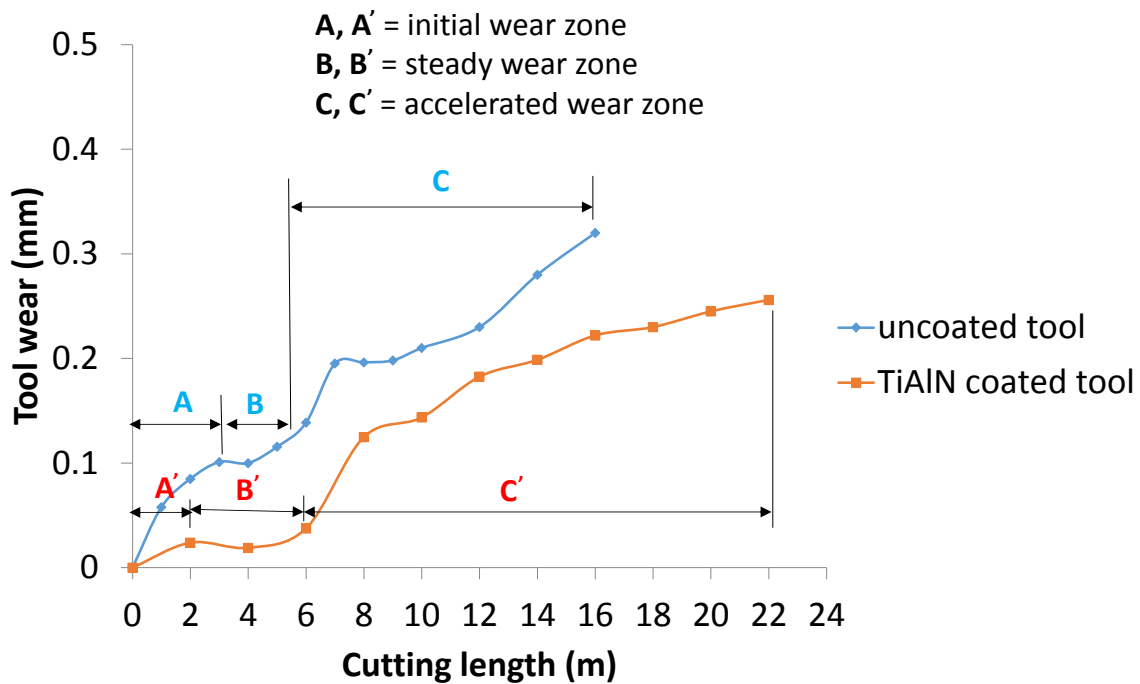


Fig. 3 Comparison of uncoated and TiAlN coated tool wear progress as a function of cutting length

3.2 Wear mechanisms

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2 In order to evaluate the machining performance of the cutting tools, understanding of the
3 underlying wear mechanisms is essential. Wear and wear mechanism vary with the
4 combination and interaction of the cutting tool and workpiece, in addition to cutting
5 environments. As titanium is a hard material, wear mechanisms that influence the failure of
6 carbide tools may be different from machining of other materials. As a representative, Fig. 4
7 (a) shows SEM photographs of flank wear land of the uncoated tool after cutting of 16 m. A
8 large abrasive wear land along the cutting edge is observed on the uncoated tool. As wear
9 increases, onset of tool failure is initiated by small edge chipping and/or plastic deformation
10 as seen in Fig. 4(b). This would be due to increased friction due to wear causing thermal
11 stress at the edge. Built up edges (BUE) due to adhesion between tool and workpiece
12 materials are noticed on along the cutting edge and flank land (see Fig. 4(c)), which are
13 expected to potentially further accelerate abrasion and friction between the tool and
14 workpiece, hence consequently result in increased wear.
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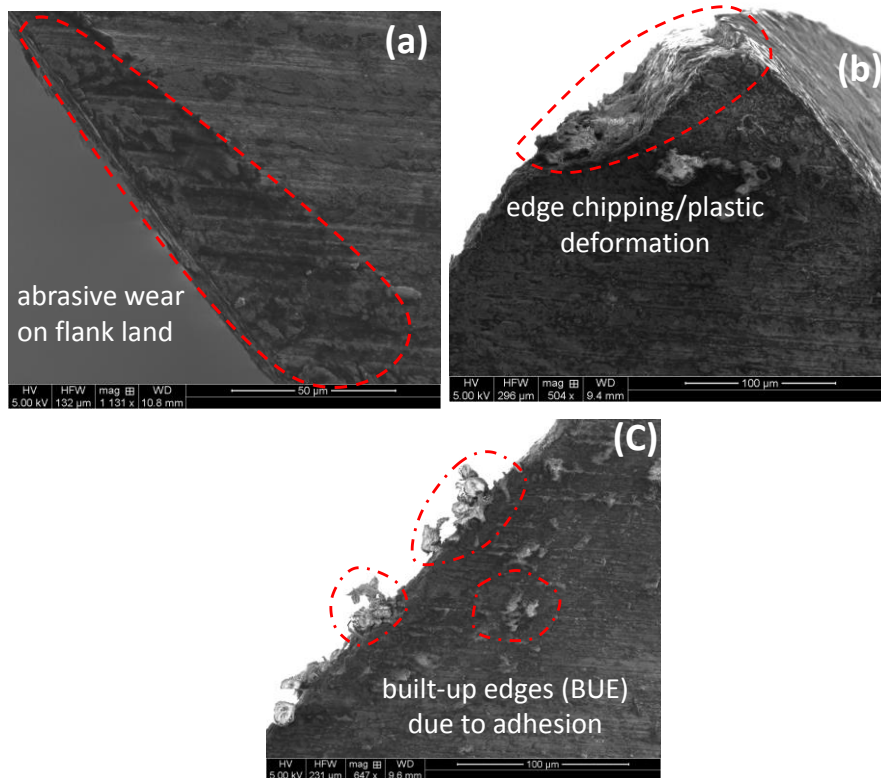
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17 At the same cutting distance, interestingly the cutting edge of the coated tool appears to be
18 very smooth with very small or minor wear marks on the flank land, as shown in Fig. 5(a).
19 Observed gradual flank wear can be due to the increased wear resistance of the TiAlN
20 coating during continuous abrasion of the tool with the workpiece. Similar progressive wear
21 on flank land for the coated tool in cutting of titanium was reported by Dhar et al. [21]. No
22 significant chipping and fracture on the cutting edge were observed; but, similar to uncoated
23 one, sticky BUEs are noticed on the cutting edge. However, it is to be noted that the coating
24 on the cutting edge appears to come off due to the continuous abrasion between workpiece
25 (including BUE) and tool (Fig. 5(b)). As reported by Konig et al. [23], accelerated adhesion
26 takes place after the coating has been removed due to prolonged cutting. In such case, the
27 adhered material is hit and squashed by the tool in the event of re-entry into the workpiece,
28 resulting in chipping and eventually to the breakage of carbide at the cutting edge. The
29 adhering metal was often noticed on the flank face rather than on the rake face. This, to large
30 extent, clearly supports our observation and analysis on wear and wear mechanism of
31 uncoated and coated carbide tools.
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34 In this study, we employed a single set of relatively conservative-medium cutting conditions
35 (speed of 80 m/min, feed rate = 0.1 mm/rev), and no severity of the tool damage or failure
36 was noticed for the coated tool even after the cutting of 22 m. However, at the cutting speed
37 of more than 100 m/min, cutting edge cracking and brittle fracture due to high stress
38 concentration because of high temperature are often regarded the major reasons for tool
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1 failure [15]. This phenomenon has been reiterated and observed by many researchers [10],
2 [11], [24]. In particular, Ghani et al. [12] recently reported that cutting of titanium at a speed
3 of 120-135 m/min is likely to induce high temperature at the cutting edge, which weakens the
4 micro-bonding between the carbide particles and their binders, thus resulting in early brittle
5 fracture at the nose of the tool.
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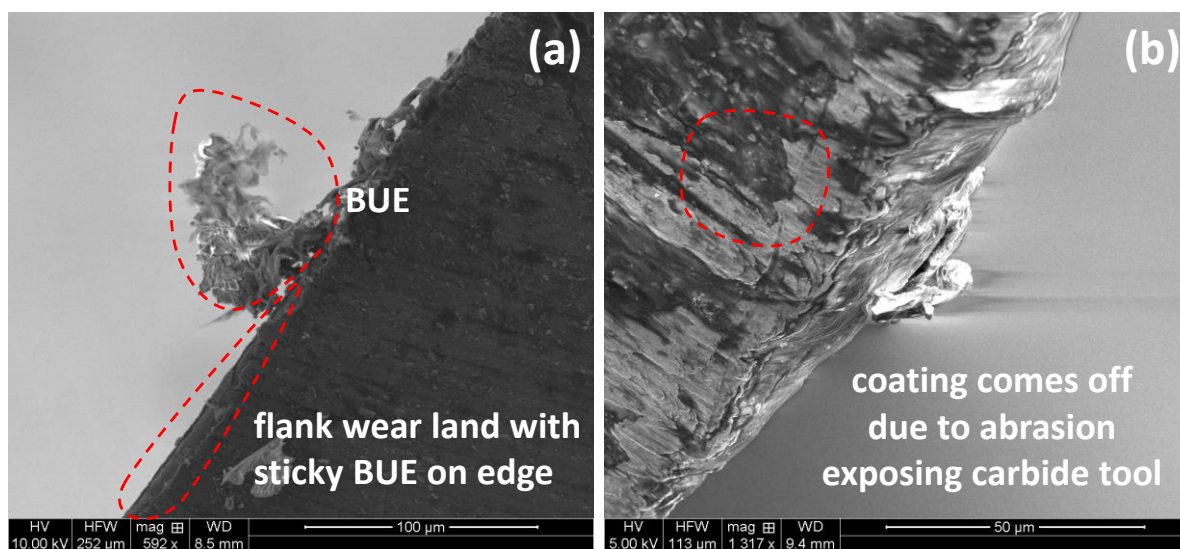
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9 As seen in Fig. 5(b), TiAlN coating is potentially expected to be diffused and taken away
10 from the cutting edge, and the part of the tool which is engaged with the workpiece thus
11 becomes uncoated, causing the tungsten carbide being exposed to the cutting zone. This can
12 be further supported by the presence of fairly large amount of Ti on the tool edge detected by
13 EDX, as illustrated in Fig. 6. Diffusion of coating materials into workpiece/chips resulting in
14 tool failure is reported by researchers. In an extensive study by Odelros and Stina [25], EDX
15 analysis revealed a high content of Ti in particles adhered to the cutting tool, indicating the
16 detected Ti content is due to the underlying chemical reaction between the coating material
17 and titanium alloy. It is to be noted that these adhered layer of materials (often termed as
18 BUE) further cause abrasion between the tool and cutting chips/workpiece, hence resulting in
19 an accelerated wear on flank face of the tool. Similar wear mechanisms with an extensive
20 EDX analysis of chemical compositions and their diffusions of BUE materials in cutting of
21 titanium alloys were reported by e.g. [26]. Note that, in this study, crater wear land is not of
22 the interest as at low cutting speed, flank wear is often regarded as the dominant indicator of
23 tool wear performance [10].
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27 In a dry cutting, reduction of cutting induced temperature is essential to sustain tool life.
28 While the use of cutting lubricants and coolants is found, to certain extent, to minimize the
29 cutting temperature, the design of heat and wear resistant tool material with low friction
30 needs to be developed. In addition, proper choice of cutting parameters including cutting
31 speed and feed rate, which are shown to be the most dominating factors in influencing the
32 tool failure, needs to be sought in order to improve the machinability of titanium alloys.
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Fig. 4 Wear land and mechanism of uncoated carbide tool at a cutting length of 16 m



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Fig. 5 Wear land and mechanism of TiAlN coated carbide tool at a cutting length of 16 m

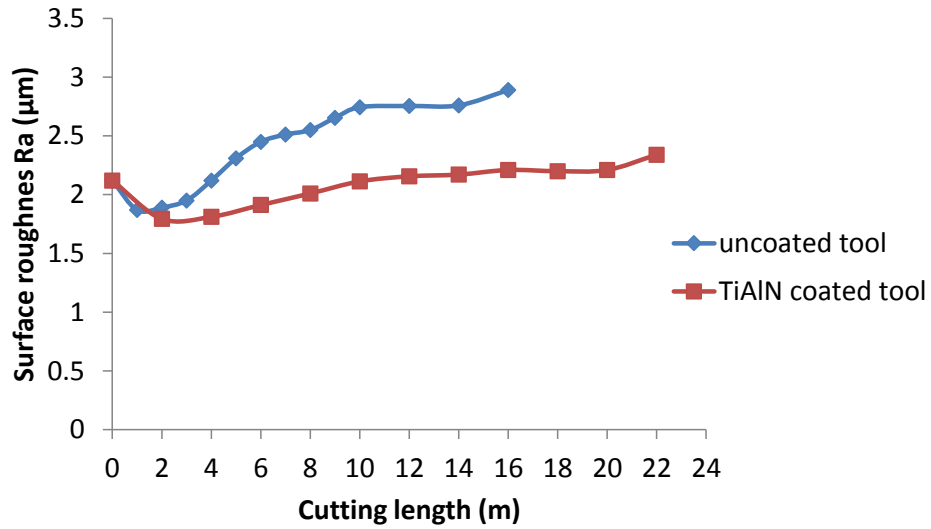


Fig. 7 Comparison of surface roughness between uncoated and TiAlN coated tools

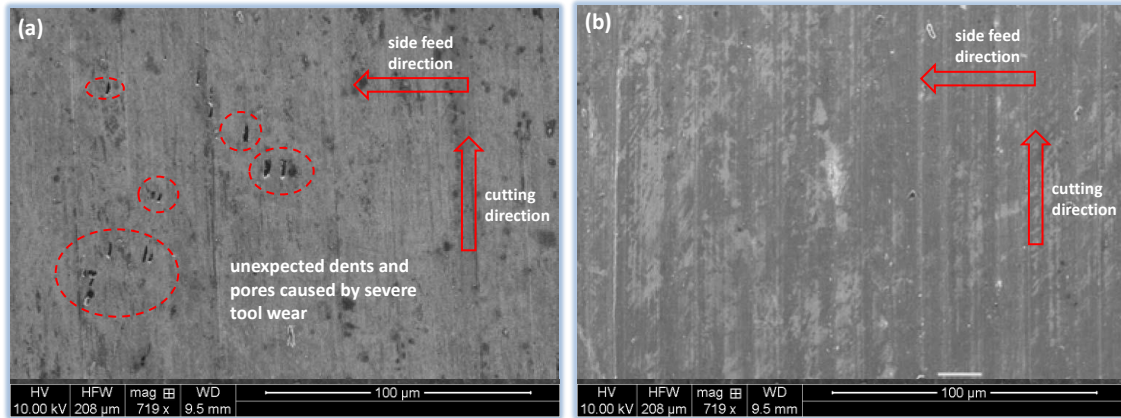


Fig.8 SEM photos of machined surface topology at a cutting distance of 16 m for (a) uncoated tool and (b) TiAlN coated tool

Further, cutting chips or swarf generated at the cutting zone were collected and observed by the optical microscope. **Figure 9** shows the chips generated by uncoated and TiAlN coated tools at a cutting distance of 16. More discontinuous and fracture chips are noticed for the uncoated tool (**Fig. 9(a)**). Further, burnt chips with blue colour are observed. This can be due to the heat generated at the cutting zone of the blunted tool due to wear. On the other hand, the coated tool generates fairly continuous and unbroken chips (**Fig. 9(b)**). Interestingly, chips generated by both tools appear to be saw tooth or serrated type, as can be seen in **Fig. 9(c)**. Mechanisms and modelling of serrated chips generated during cutting of titanium alloys were widely well reported and confirmed by many research works in literature [28]–[31]. It is shown that the small initial chip thickness and large rake angle affects the generation and

1 geometry of regular serrated chips [32]. While the initial thickness is related to the feed rate
2 to be chosen, the actual chip thickness during the cutting can be affected by the cutting edge
3 of the tool associated. Therefore, it is possible that the severe tool wear at the cutting edge
4 may influence the geometry of serrated chips. Hence, in order to minimize the serrated
5 chipping, tool wear must be regulated to the acceptable level without sacrificing the
6 machining productivity. With this aim, one possible solution is to develop prediction model
7 of energy efficient machining of titanium alloys by controlling inherent cutting temperature
8 and vibration generated [33], which will allow choosing the optimum machining conditions
9 including cutting parameters to enhance the tool life.
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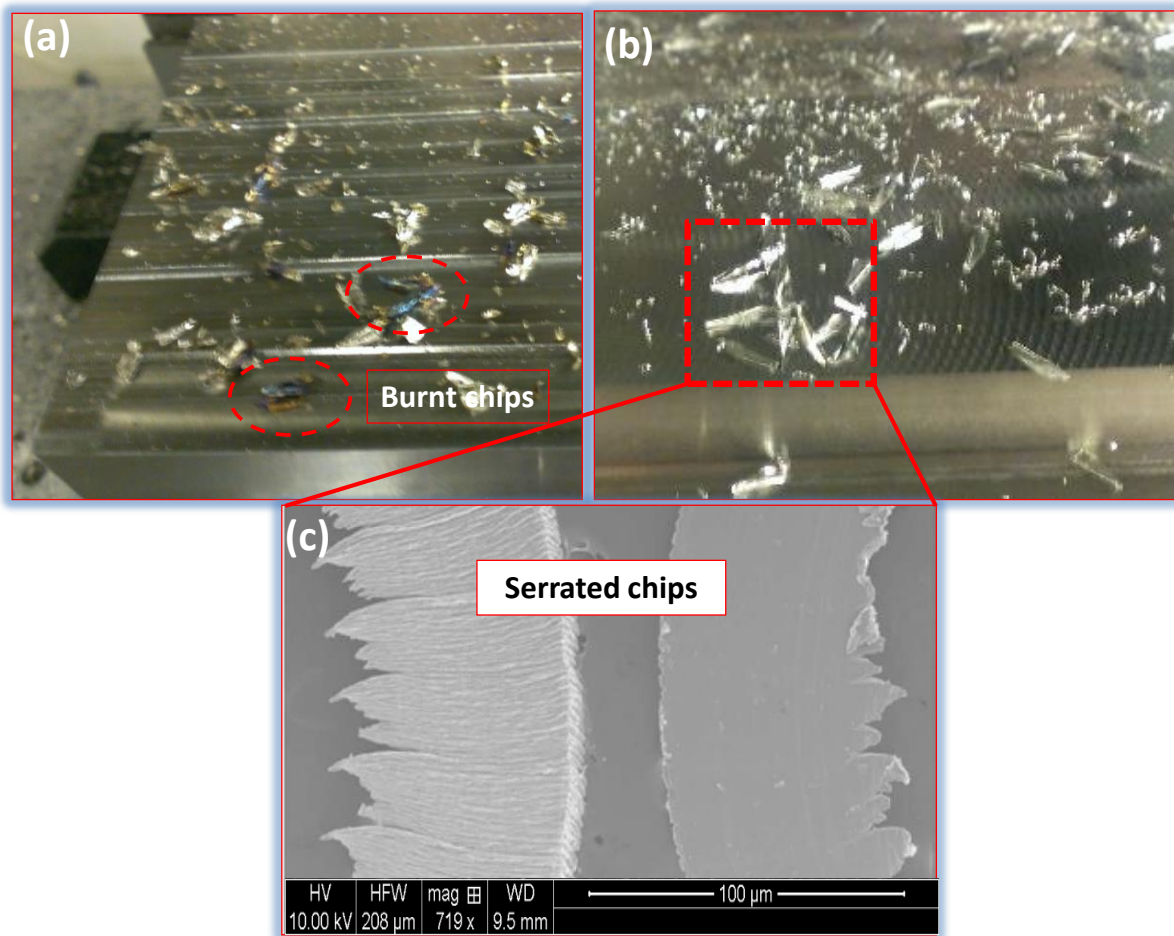


Fig. 9 Optical microscopic photos of chips formed by (a) uncoated tool, (b) TiAlN coated tool at a cutting length of 16 m and (c) magnified SEM photo of the chips

4. Conclusions

This paper is focused on an investigation and comparison of wear progression and wear mechanisms of uncoated and TiAlN coated tungsten carbide tools in high speed cutting of Ti6Al4V alloy. The following are the key conclusions drawn from this study.

- The TiAlN coated tool exhibits improved tool life with approximately 44% lower flank wear than the uncoated tool at a cutting distance of 16 m.
- A more regular progressive abrasion between the flank face of tool and workpiece is found to be the underlying wear mechanism and small edge chipping and/or plastic deformation for prolonged cutting are noticed for the uncoated tool.
- Diffusion as a form of BUEs due to the chemical reaction between the coating and the workpiece materials at high cutting temperature is shown to cause the removal of coating from the tool, and weaken the cutting edge, which may result in further acceleration of potential failures.
- The TiAlN coated tool generates smooth machined surface with a 31% lower roughness (R_a) over the uncoated tool. As is expected, both tools generate the serrated chips; however, burnt chips with blue colour are noticed for the uncoated tool as the cutting continues further.

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