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Chapter

The Comparison of Cutting Tools for High Speed Machining of Ti-6Al-4V ELI Alloy (Grade 23)

Chakradhar Bandapalli, Bharatkumar Mohanbhai Sutaria and Dhananjay Vishnu Prasad Bhatt

Abstract

Green technology is one of the major aspects in order to reduce the global pollution content from manufacturing industries. There is a need to investigate the different available tools for high-speed micromilling process of advanced alloys to achieve desired surface finish without traditional coolants. In this chapter, tool wear investigation of uncoated and PVD-coated AlTiN, TiAlN tungsten carbide end mills in high-speed micro-end milling of alpha + beta Ti-6Al-4V ELI titanium alloy (Grade 23) under dry cutting conditions was presented. A comparison for machining performance with the three tools is reported. Cutting force analysis was done under the considered machining input parameters for evaluating the tool condition. Tool wear observation was done by SEM analysis. EDX analysis was performed to know the material constituents and wear mechanisms on the cutting tool tip. It is found that diffusion, oxidation, adhesive and abrasive wear mechanisms were the major phenomena taking place on the cutting edge of micro end mills. From the comparison of cutting tools for machining Grade 23 titanium alloy, it was found that TiAlN tools performed better than AlTiN and uncoated tungsten carbide tools.

Keywords: green technology, micro-end milling, PVD-coated AlTiN and TiAlN tungsten carbide end mills, tool wear, titanium alloys, and uncoated tungsten carbide end mills

1. Introduction

Titanium and its alloys materials are broadly used in applications like air frame components, medical implants/devices, surgical instruments, ballistic armour, space vehicles/structures, missile components, navy ship components, chemical processing equipment, hydrocarbon refining/processing, hydrometallurgical extraction/electrowinning offshore hydrocarbon production, desalination, brine concentration/evaporation, power generation, automotive, mining, railways and sporting goods. The large variety of application is due to its desirable properties, mainly the relative high strength combined with low density and enhanced corrosion resistance. In terms of biomedical applications, the properties of interest are biocompatibility, corrosion behaviour, mechanical behaviour, process ability and availability [1–5].

In machining of brittle and ductile materials, selection of available tools with different grades is a complex matter. Economics and quality of the machining are dependent on tool wear. Evaluation and measurement of tool wear in micromilling are challenging compared to the conventional machining process. In high-speed micromilling based on the surface finish requirement on the desired work material, tools with smaller diameter, that is, two flute and four flute end mills, are used for superfinishing operation. Two, four and more flute tools having larger tool diameter are used for the roughing operation. Tool wear occurrence in four flutes is lower than two flutes as the cutting and load bearing capacity is higher for four flutes in roughing and super finishing operations. In super finishing, at high spindle speeds for a slotting operation which is single pass cutting, the usage of micro-end mills is limited, maybe two to three slots. Burr formation, cutting forces, surface roughness and acoustic emission signals observation and analysis information provide the tool wear prediction in high-speed micro-end milling. Tool material properties and machining parameters decide the tool wear formation. Tool wear of a different kind takes place in micromilling because of small cutting edge, microstructure variation, difference in work and tool material phases, deformed chips, wrong rake angle tools selection shape and a number of flutes, friction and stress induced [6–9] on the tool.

Komanduri and Reed [10] investigated the cutting performance of carbide grades and new cutting geometry in turning operation of titanium alloys. They observed that prolonged tool life in machining Ti alloys can be obtained at high clearance angle and high negative rake angle. Kitagawa et al. [11] investigated the temperature and wear of cutting tools in high speed machining of Ti-6Al-6V-2Sn and found that temperature plays the major role for tool wear during machining. According to Jawaid et al. [12], CVD-coated tools performed well during face milling of Ti-6Al-4V than PVD tools. They observed nonuniform flank wear pattern on both the tools and found that coating delamination, diffusion, attrition, adhesion wear mechanisms were responsible factors. Liu et al. [13] investigated cutting forces and surface quality in micromilling of TC4 titanium alloy. They found that surface quality of machined surface is prone to the influence of burrs and residual chips. Nouari et al. [14, 15] investigated CVD tools and uncoated tools performance in machining titanium alloy Ti-6242S and they observed almost equal performance of both tools. They observed similar physical phenomenon while machining as mentioned by Jawaid et al. [12]. Rahman et al. [16] presented a review on high-speed machining of titanium alloys especially in turning and milling operations. They discussed the performance of coated and uncoated tungsten carbide tools, polycrystalline diamond (PCD) tools, cubic boron nitride (CBN) tools, and binderless cubic boron nitride (BCBN) tools in terms of cutting forces generation and tool wear. They found that BCBN tools performed well in high-speed machining conditions and traditional tools in moderate cutting speed conditions. Ginta et al. [17] investigated tool wear morphology and chip segmentation in end milling of titanium alloy Ti-6Al-4V using uncoated WC-Co inserts. They also performed modelling and optimization of tool life and surface roughness. They observed abrasion/attrition, plastic deformation and diffusion wear processes. They found that combination of high cutting speed and feed substantially increases the stress near the nose and flank zone, generates high temperature and encourages high wear rate.

Schueler et al. [18] investigated the burr formation mechanisms and surface characteristics in micro-end milling Ti-6Al-4V and Ti-6Al-7Nb titanium alloys. Large areas were machined to observe the microstructure on the surface and the influence on surface quality. Up milling and down milling at the sidewalls were compared. They found that down milling is better than up milling. Arrazola et al. [19] investigated and compared the cutting forces, tool wear and chip geometry in the machining of ($\alpha + \beta$) Ti-6Al-4V and near-beta (β) Ti555.3 titanium alloys. They found that adhesive

and diffusion wear on cutting tools when machined with both the grades of titanium alloys. Specific feed force and cutting force are higher for Ti555.3 alloy than Ti-6Al-4V alloy. Chip formation observed was segmented with and without adiabatic shear zones in Ti-6Al-4V alloy and narrow adiabatic shear bands for Ti555.3 alloy. Malekian et al. [20] investigated tool wear monitoring in micromilling processes to avoid the failure of tools during the considered machining conditions. Tool edge radius and wear were observed and measured using vision system and as well as gathered sensor signals of acoustic emission, acceleration and force data. These data were interpreted offline using adaptive neuro-fuzzy inference ystem and compared with experimental wear results that were agreeable. Smith et al. [21] investigated surface quality and tool wear in micromilling of Ti-6Al-4V using monocrystalline CVD diamond cutting edges with preferential crystallographic orientation. The analyses of tool wear and workpiece surface quality proved that monocrystalline CVD diamond cutting edges with preferential crystallographic orientation along rake and clearance faces can be successfully utilised for interrupted cutting operations (i.e., micromilling) of alloys which react with diamond, such as those based on titanium. Zhang et al. [22] investigated the cutting forces and tool wear variations during high-speed micro-end milling of titanium alloy (α + β) Ti-6Al-4V using uncoated cemented tungsten carbide tools. They found that due to adhesion, abrasion and diffusion process, tool wear takes place and cutting force component Fy, in the considered experiment, has a positive relationship with the tool wear propagation.

Ozel et al. [23–25] carried out experimental investigation and finite element simulation with CBN tools and uncoated tools in the micromilling of Ti-6Al-4V. They found that larger the feed rate, the higher the burr formation, surface roughness, temperature generation, cutting forces and tool wear. CBN tools had less tool wear and temperature formation than uncoated tools. Wyen et al. [26] investigated the influence of the cutting-edge radius on surface integrity in slot milling of Ti-6Al-4V with different edge radius tools. As the cutting temperature and kinematics influence the up and down machining processes, they thoroughly researched on cutting edge radius owing to the temperature generation. They found that down milling is better than up milling for surface roughness and burr formation which gradually increase with increasing cutting-edge radius from the measurements of residual stress and compressive stress generation. Durul and Ozel [27] presented review on machining-induced surface integrity in titanium and nickel alloys. They reported detailed performance of the different tools, tool wear behavior, burr formation, surface topography and FEM simulations. Bajpai et al. [28] investigated surface quality and burr formation in HSMEM of Ti-6Al-4V and it was found that as cutting speed, feed rate and depth of cut increased, then smoother surface finish can be achieved. Burr formation is increased due to increment in depth of cut. Hou et al. [29] investigated the influence of cutting speed on tool wear, flank temperature and cutting force in macro-end milling of titanium alloy Ti-6Al-4V using PVD-coated TiN/TiAlN and uncoated tungsten carbide tools. They found that high cutting forces were generated when cutting speed is increased and increment in mean flank temperature for the coated cutting tools, whereas it is almost constant for uncoated tools. At higher cutting speeds, no abrasion and fatigue wear were observed for uncoated tools and in contrast with coated tools. Kim et al. [30] discussed the machining input parameters influence and found that spindle speed and feed rate were the most influencing factors for generating cutting forces and burr formation on Ti-6Al-4V. Pervaiz et al. [31] presented a review on influence of tool materials on machinability of titanium- and nickel-based alloys. Ceramic, PCD, CBN, boronized carbide tools and high pressurised coolant supply show good results for machining. They observed that in experimental studies that high pressurised coolant supply reduces cutting temperature and improves chip

breakability which results in improved tool life. Increase in the pressure of coolant supply also improves tool life. Notch wear was reduced by increasing coolant supply pressure when machining titanium alloys.

Hassanpour et al. [32] investigated the cutting force, microhardness, surface roughness and burr size in micromilling of Ti-6Al-4V using minimum quantity lubrication. They found that cutting speed and feed per tooth significantly affect the surface roughness. Bandapalli et al. [33] have investigated the influence of machining parameters in high-speed micro-end milling of commercially pure titanium Grade 2 and found that cutting forces and surface roughness formation increases at high spindle speed by increasing feed rate and depth of cut. Ghani et al. [34] investigated the wear mechanism of uncoated carbide cutting tool in milling of aluminium metal matrix composite (AlSi/AlN MMC), PVD-coated TiAlN/AlCrN tool in milling of Inconel 718 and uncoated tool in turning of Ti-6Al-4V ELI. They found that tools failed primarily on two main areas of the flank and rake faces for cutting the Inconel 718 and titanium alloy. Wear such as crater, nose wear, abrasion, notching, fracturing and cracking were observed. In machining AlSi/AlN MMC, the tools mainly failed due to the uniform flank wear that was caused by abrasion.

However, research findings related to considered machining parameters in high-speed micro-end milling (HSMEM) of titanium alloys for comparison and evaluation of uncoated, PVD-coated TiAlN and AlTiN tools are inadequate. The purpose of this research work is to evaluate the performance of tools like uncoated and physical vapour deposition (PVD)-coated TiAlN and AlTiN tools in terms of tool wear formation in HSMEM of alpha + beta Ti-6Al-4V ELI titanium alloy (Grade 23). The goal was to improve the quality or productivity of the specific machining process based on empirical experiments using a variety of speeds, feeds and depth of cut. This work is categorised into four sections, first with an introduction. Experimental details were discussed in Section 2. Results and discussion were presented in Sections 3 and 4 and finally Section 5 is presented with conclusions.

2. Experimental details

Standardised experimental tests are carried out on high-speed micromachine setup as shown in **Figure 1**. The work material considered was Ti-6Al-4V ELI titanium alloy (Grade 23) of dimensions 60 × 40 × 4 mm as shown in **Figure 2**. Chemical composition and properties of the work material are shown in **Tables 1** and **2**. Experimental tests conducted are shown in **Table 3**. Two flute uncoated tungsten

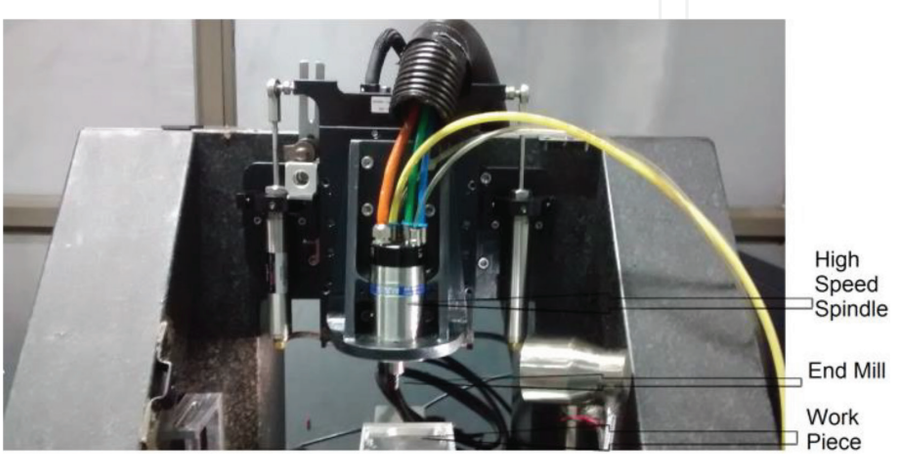


Figure 1.
High speed micromachine.



Figure 2.
Ti-6Al-4V ELI titanium alloy (Grade 23).

Properties	Metric
Tensile strength	860 MPa
Yield strength	790 MPa
Poisson's ratio	0.342
Elastic modulus	113.8 GPa
Shear modulus	44.0 GPa
Elongation at break	15%
Hardness Rockwell	35
Density	4.43 g/cm^3
Melting point	1604–1660°C

Table 1.
Mechanical and physical properties of Ti-6Al-4V ELI titanium alloy (Grade 23).

Element	wt%
Titanium, Ti	88.09–91
Aluminium, Al	5.5–6.5
Vanadium, V	3.5–4.5
Iron, Fe	≤0.25
Carbon, C	≤0.080
Nitrogen, N	≤0.030
Hydrogen, H	≤0.0125
Other	≤0.50
Total	100

Table 2.
Chemical composition of Ti-6Al-4V ELI titanium alloy (Grade 23).

carbide end mills and physical vapour deposition-coated TiAlN and AlTiN tungsten carbide end mills of diameter 500 μm supplied by IND-SPHINX Axis tools were used in this work as shown in **Figure 3**. The total length of each machined slot was 12 mm. Tool over hang length considered was 18 mm. The width of cut is 500 μm as the process is slot milling operation. Cutting edge radius of tool identified is 2.71 μm through SEM. Coating of the material as specified by the IND-SPHINX Axis tools is

Exp. no	Spindle speed (rpm)	Feed (μm/ tooth)	Depth of cut (mm)	Cutting force (N)		
				Uncoated	TiAlN	AlTiN
1	30,000	2	0.02	0.37	0.34	0.33
2	30,000	5	0.02	0.39	0.34	0.31
3	30,000	8	0.02	0.41	0.36	0.34
4	30,000	2	0.06	0.46	0.63	0.62
5	30,000	5	0.06	0.57	0.68	0.67
6	30,000	8	0.06	0.69	0.81	0.66
7	30,000	2	0.1	0.75	0.76	1.5
8	30,000	5	0.1	0.82	0.88	1.55
9	30,000	8	0.1	1.01	1.16	1.56
10	70,000	2	0.02	0.09	0.14	0.13
11	70,000	5	0.02	0.21	0.21	0.21
12	70,000	8	0.02	0.37	0.29	0.29
13	70,000	2	0.06	0.15	0.26	0.22
14	70,000	5	0.06	0.31	0.31	0.38
15	70,000	8	0.06	0.47	0.40	0.41
16	70,000	2	0.1	0.21	0.35	0.57
17	70,000	5	0.1	0.43	0.46	0.54
18	70,000	8	0.1	0.56	0.58	0.63
19	110,000	2	0.02	0.12	0.13	0.22
20	110,000	5	0.02	0.31	0.28	0.28
21	110,000	8	0.02	0.49	0.34	0.28
22	110,000	2	0.06	0.16	0.15	0.19
23	110,000	5	0.06	0.37	0.27	0.36
24	110,000	8	0.06	0.56	0.37	0.37
25	110,000	2	0.1	0.18	0.16	0.25
26	110,000	5	0.1	0.46	0.34	0.61
27	110,000	8	0.1	0.67	0.41	0.77

Table 3.
Resultant cutting forces for uncoated, coated TiAlN and AlTiN WC tools.



Figure 3.
Micro-end mills.

2–6 μm. Rake angle of the tool is +5°. Static run-out of the tool was measured as 3 μm. No structural vibrations were observed under considered machining conditions. Chip thickness observed is about 3 μm. Machining time was 10–12 s for 30,000 rpm, 6–8 s for 70,000 rpm and 3–5 s for 110,000 rpm.

Parametric experiments, full factorial design 3^3 = 3 factors, each with three levels, 3^3 = 27 total runs were conducted for determining the effect of the process parameters on the cutting force and tool wear. Three levels of tool rotation speed—30,000, 70,000 and 110,000 rpm, that is, cutting velocity of 47, 110 and 173 m/min, three levels of feed rate—2, 5 and 8 μm/tooth and three levels of depth of cut—0.02, 0.06 and 0.1 mm were selected in these experiments. Two sets of experimentation, that is, one original and one repetition were performed in which total number of machined slots are—162 (27 × 2 × 3 tool types). Six uncoated tools for 54 experiments, 6 TiAlN tools for 54 experiments and 6 AlTiN tools for 54 experiments were used in this experimentation. End mill was changed with new one after machining nine slots on the workpiece for verification and observation of cutting forces and tool wear. Coated tools were selected because they provide high wear resistance, withstand mechanical and thermal shock, plastic deformation, act as barrier towards wear formation, reduce subsurface defects on workpiece by generating less heat, high hot hardness, chemical inertness to reduce development of built-up edge and occurrence of coating delamination, less burr formation and ability to withstand high cutting forces. In accordance with the above view, uncoated and PVD-coated TiAlN and AlTiN tungsten carbide end mills were considered in the present research work. Tool wear was examined using HITACHI-S3400N scanning electron microscope (SEM) equipped with energy dispersive spectroscope (EDS).

3. Results and discussion

3.1 Cutting force analysis

Micro-end milling is one of the most commonly used machining processes and has more complex geometry due to its rotating tool, multiple cutting edges and intermittent cutting action. Cutting forces are the main cause of the deformations of machine tool structures and workpieces resulting in form errors and tolerance violations. Although they may affect the structural components of a machine tool distributed in a large space, cutting forces are generated in a very small area at the work-tool interface. A cutting origin was set through a CCD camera because the tool diameter was extremely small and direct origin setting with naked eye was difficult and could result in significant errors. Cutting forces in three directions F_x, F_y and F_z measured using tool dynamometer, and from the signal analyser, the forces were interpreted in the computer. Resultant cutting forces were calculated by Eq. (1). Experimental results of resultant cutting forces are shown in **Table 3**.

$$F_R = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

3.1.1 Micromilling with uncoated tools

At 30,000 rpm, if depth of cut and feed is varied, then resultant cutting force increased by 63% as shown in **Figure 4(a)**. At 70,000 rpm, if depth of cut and feed is varied, then resultant cutting force increased by 87% as shown in **Figure 4(b)**. At 110,000 rpm, if depth of cut and feed is varied, then resultant cutting force increases by 83% as shown in **Figure 4(c)**.

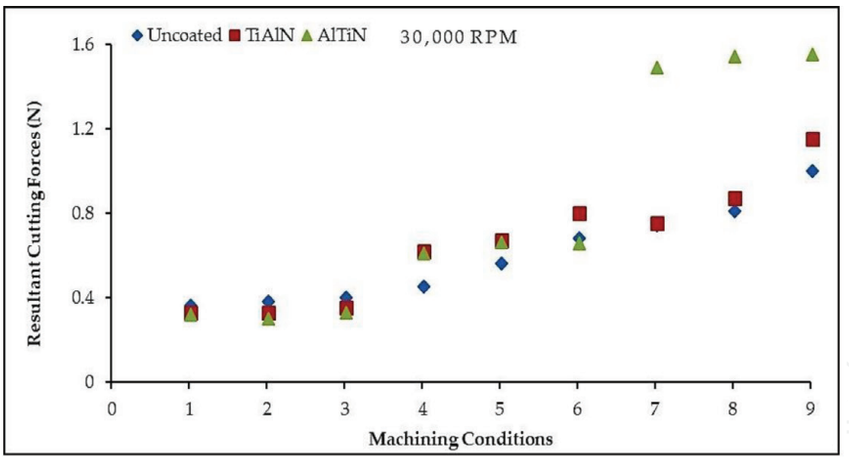
3.1.2 Micromilling with TiAlN tools

At 30,000 rpm, if depth of cut and feed is varied, then resultant cutting force increases by 81.7% as shown in **Figure 4(a)**. At 70,000 rpm, if depth of cut and feed is varied, then resultant cutting force increases by 85.14% as shown in **Figure 4(b)**. At 110,000 rpm, if depth of cut and feed is varied, then resultant cutting force increases by 78% as shown in **Figure 4(c)**.

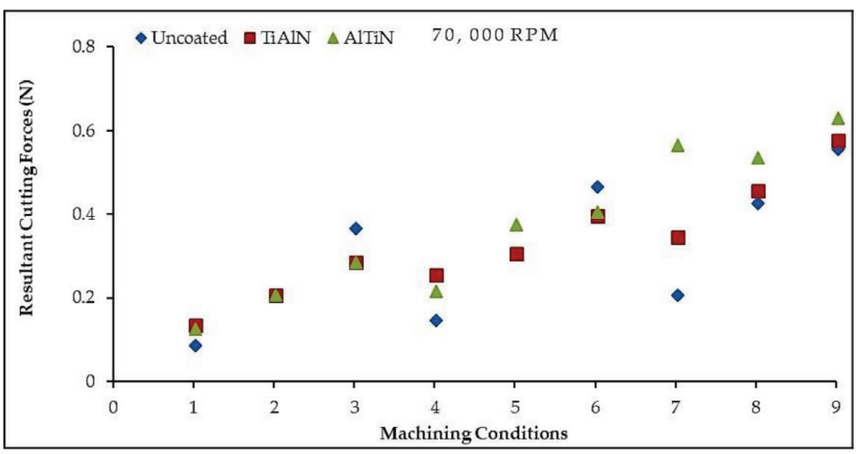
3.1.3 Micromilling with AlTiN tools

At 30,000 rpm, if depth of cut and feed is varied, then resultant cutting force increases by 82.6% as shown in **Figure 4(a)**. At 70,000 rpm, if depth of cut and feed is varied, then resultant cutting force increases by 87% as shown in **Figure 4(b)**. At 110,000 rpm, if depth of cut and feed is varied, then resultant cutting force increases by 85% as shown in **Figure 4(c)**.

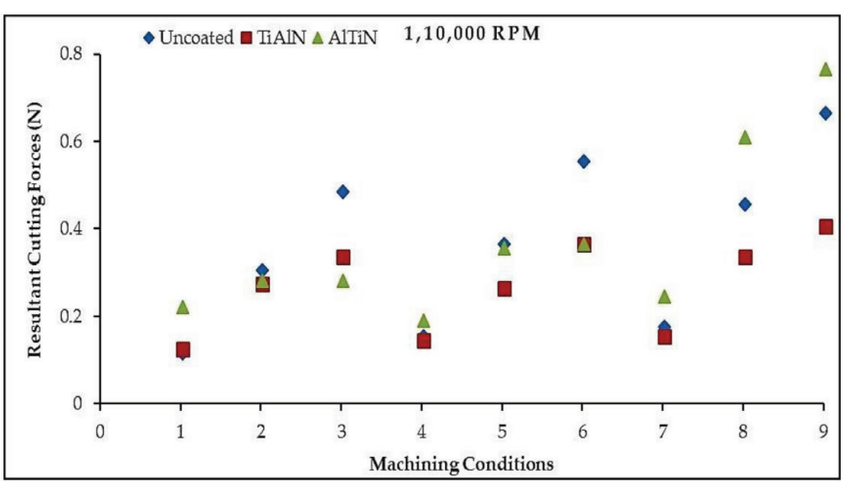
From the experimentation, it is observed that the resultant cutting force increase might be due to the increment in feed rate and depth of cut, leading to more chip formation, high contact between tool and chip, high-temperature formation by shearing and ploughing action reducing the yield strength of work material. It was observed that when spindle speed is increased, while the depth of cut and feed rate is kept at low, then cutting force generated was less. When depth of cut and feed rates are reduced, the chip load encountered in the process becomes the same order of magnitude as the grain size of many alloys. The cutting-edge radius of the end mill is comparable in size to the chip thickness. As a result, no chip is formed when the chip thickness is below the minimum chip thickness and instead part of the work material plastically deforms under the edge of the tool and the rest elastically recovers. This change in the chip formation process, known as minimum chip thickness effect and the associated material elastic recovery cases, increased cutting forces and surface roughness. Observed irregularity on the machined surface due to the plastic side flow and burr formation seem to suggest that the tool workpiece interaction is more likely to be elastic-plastic in nature. Due to the increment in feed rate, depth of cut and cutting speed, the tool wear and cutting-edge distortion took place that leads to more cutting force requirement to remove the material. At 30,000 rpm, uncoated tools performed better than both the coated tools. Uncoated tools produced less cutting force compared to coated tools because of tools stability and resistance to wear. At 70,000 rpm, 0.02 and 0.06 mm depth of cut with feed 2–8 μm/tooth, the uncoated tool required more cutting force to remove the material rather than both the coated tools. At 70,000 rpm, 0.1 mm depth of cut with feed 2–8 μm/tooth, the uncoated tool is found to generate less cutting force than both the coated tools. At 110,000 rpm, coated TiAlN tools are better performed than coated AlTiN and uncoated tools, which is due to increase in cutting temperature in the shear zone, thus reducing the yield strength of the workpiece material, chip thickness and tool-chip contact length. If coated TiAlN and coated AlTiN tools are compared, then performance of TiAlN tools is better. Depending on the particular parameters during machining processes, uneven phenomenon (sudden tool or spindle vibration, sudden workpiece movement) occurs, leading to increase of cutting forces. SEM and EDS analyses are performed to identify the wear and its formation mechanism on two flutes of each tool, that is, uncoated and PVD-coated AlTiN, TiAlN tungsten carbide end mills as shown in **Figures 5** and **6**. Tool wear on particular end mill is observed using SEM after machining nine slots for each set of spindle speed as shown in **Figures 7–12**. Tool wears measured on each cutting flute in two series of experiments have been considered and average values are reported as shown in **Figure 13**. Coated TiAlN tool wear was high at spindle speed



(a)



(b)



(c)

Figure 4.
Comparison of (a) uncoated, (b) coated TiAlN and (c) AlTiN WC tools for resultant cutting force (N) at independent spindle speed (rpm), feed (μm/tooth), depth of cut (mm).

30,000 rpm machining conditions than uncoated and coated AlTiN tools. Uncoated tools produced less wear than both the coated tools at spindle speed 70,000 rpm machining conditions. Coated TiAlN tools produced less wear than AlTiN-coated and uncoated tools at spindle speed 110,000 rpm machining conditions. Tool wear is increased for all the tools when the feed rate and depth of cut for the considered spindle speed is increased. Adhesive wear, edge chipping, flaking, coating delamination and measured tool wear that were observed under SEM at different machining conditions are shown in **Figures 7–12**.

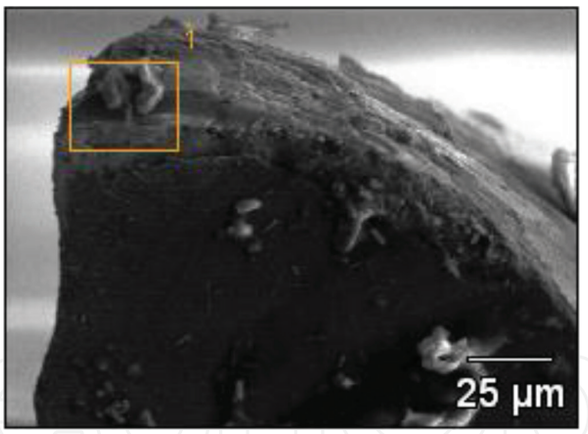


Figure 5.
SEM image of tool edge for uncoated, coated TiAlN and AlTiN WC tools with marked microzone for EDS analysis.

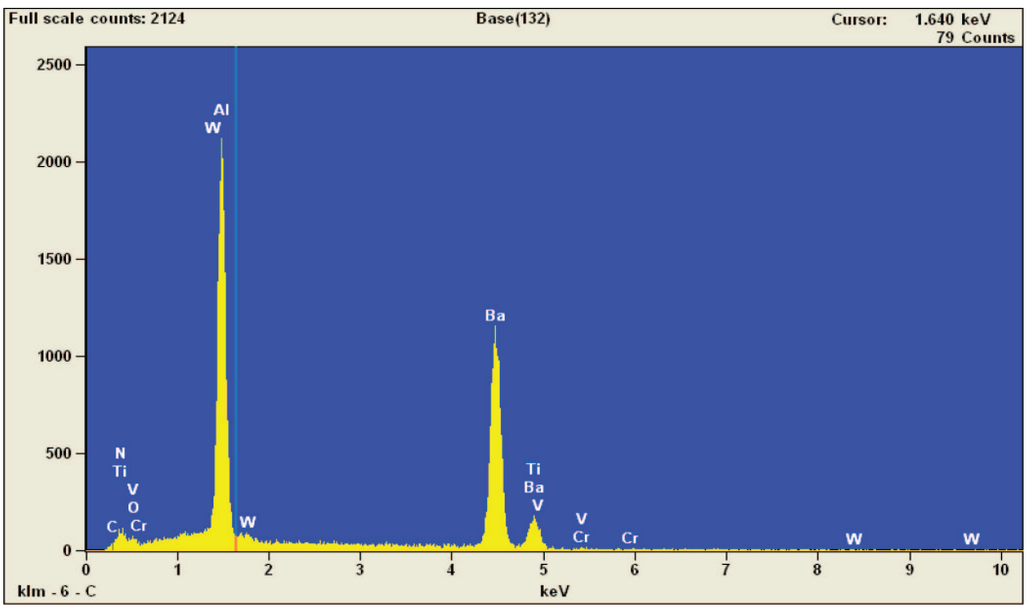


Figure 6.
EDS spectrogram.

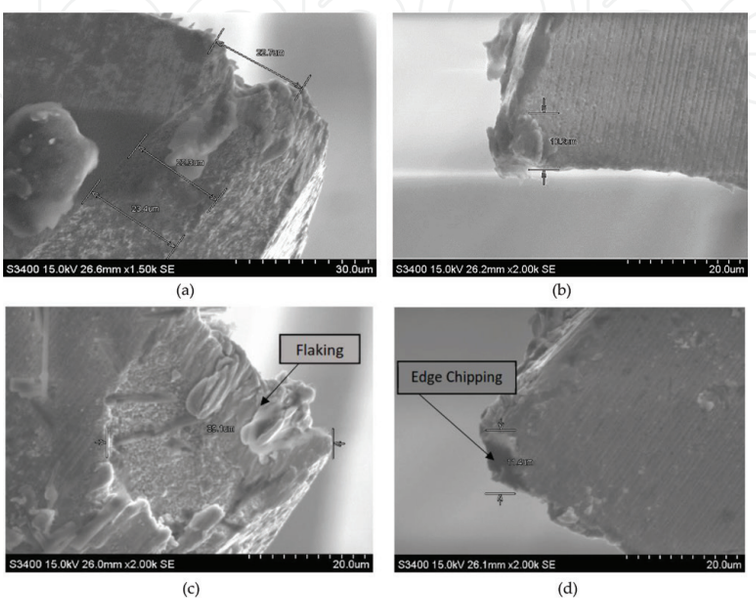


Figure 7.
(a–d) Tool wear observation for uncoated tools.

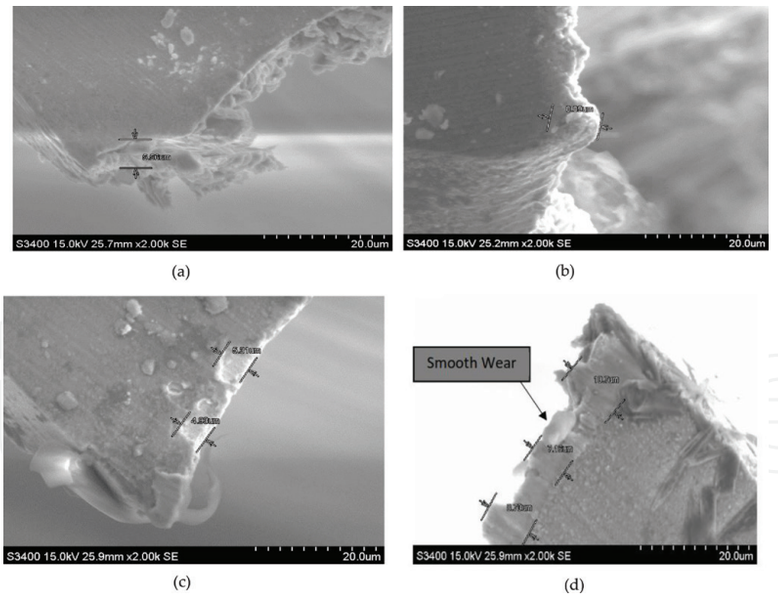


Figure 8.
Coated TiAlN tool wear at (a and b) 30,000 rpm and (c and d) 70,000 rpm.

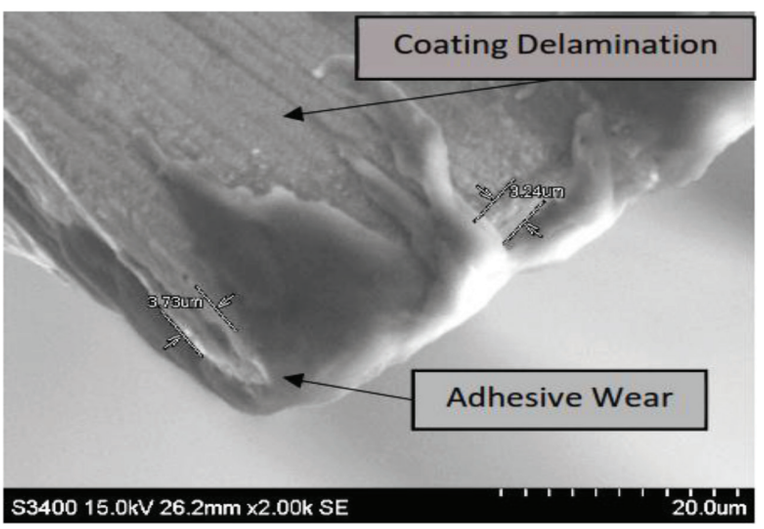


Figure 9.
Coated TiAlN tool wear at 110,000 rpm.

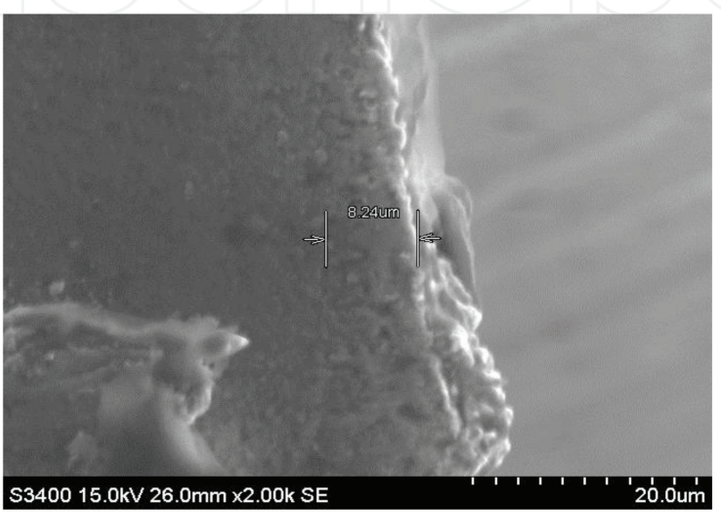


Figure 10.
Coated AlTiN tool wear at 30,000 rpm.

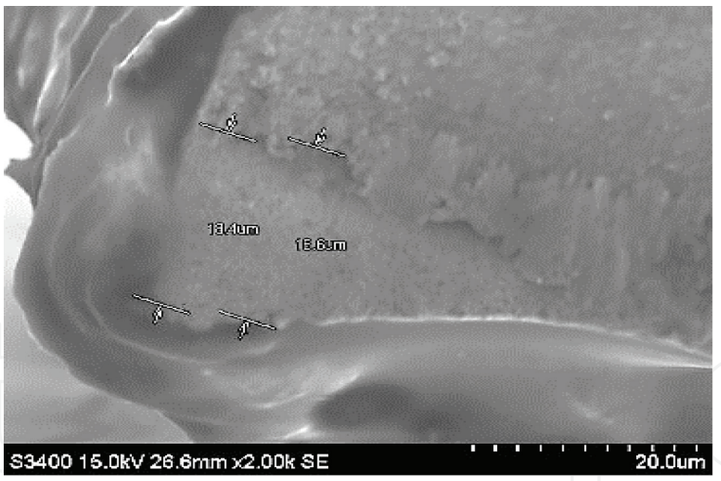


Figure 11.
Coated AlTiN tool wear at 70,000 rpm.

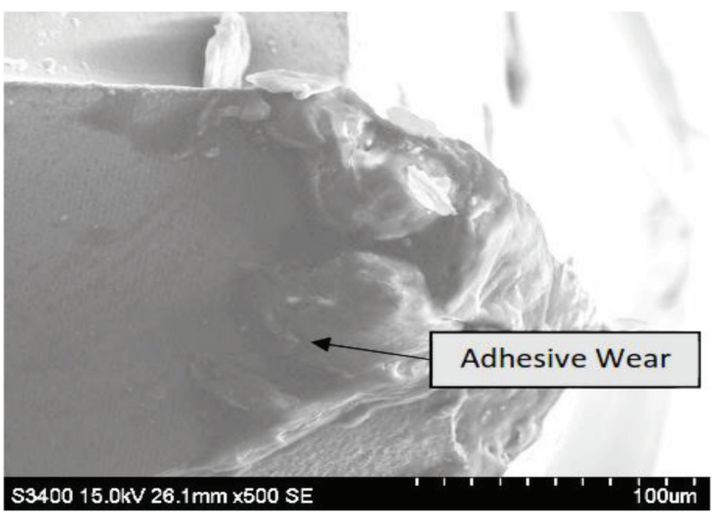


Figure 12.
Coated AlTiN tool wear at 110,000 rpm.

3.2 EDS results

The observed elemental composition on the worn surface of uncoated, coated TiAlN and AlTiN WC tools while machining the Ti-6Al-4V ELI titanium alloy (Grade 23) are shown in **Tables 4–6**.

SEM and EDS analysis for the considered machining operating parameters indicate the built-up edge, built-up layer and craters appearing at rake face and flank face of the cutting tool representing the adhesive, diffusion, abrasive and oxidation wear phenomenon on the tool surfaces. Wear confirmation process on the tool materials was discussed below.

3.2.1. SEM observations

SEM examination of the leading cutting edge for coated and uncoated tools indicates plastic deformation, adhesion wear, chipping and flaking as shown in **Figures 7–12**. In addition, coating delamination at the tool cutting edge and significant changes in the tool shape was observed under the SEM. Tool material reacts with titanium alloy by means of high chemical reaction, forming adhesive wear. During the tool-workpiece interaction, adhesive layers of tool material will break down that progresses to adhesion wear. The intimate contact between the tool and

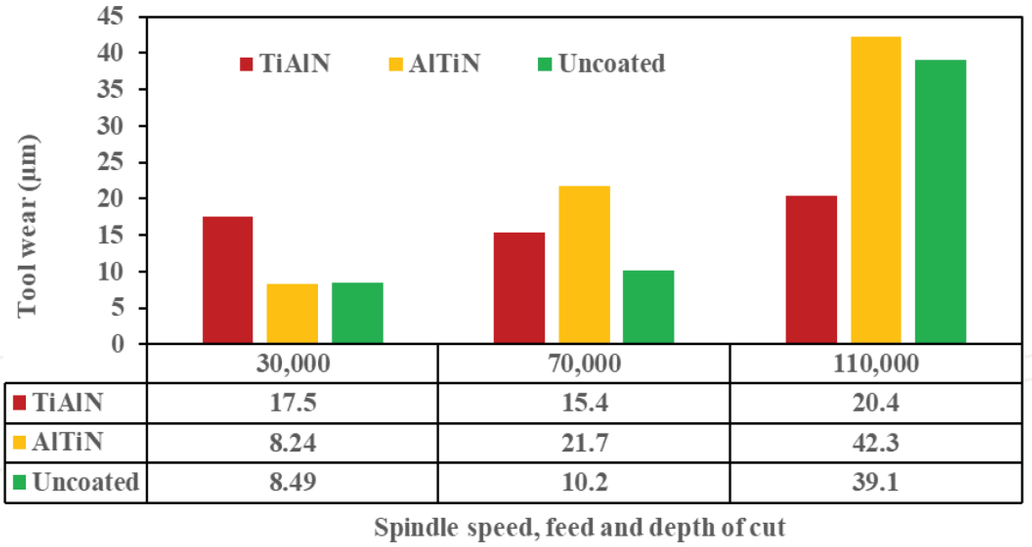


Figure 13.
Tool wear versus different machining conditions.

Maximum composition of elements	wt%
C	3–5.4
N	3–11.8
O	3–4.1
Al	0.2–0.7
Ti	0.3–10.2
V	0.3–1.1
Cr	0.3–0.8
Ba	2–9.8
W	70–84.5

Table 4.
EDS analysis results for uncoated tools.

Maximum composition of elements	wt%
C	6.8
N	9.8
O	9.4
Al	21.4
Ti	36.4
V	0.6
Cr	0.3–0.8
Ba	13.8
W	1.3

Table 5.
EDS analysis results for coated TiAlN tools.

chip interface leads to the friction and high-temperature generation, stipulating the transmission of atoms from tool material losing its hardness and ultimately breakdown happens. It appears that both coated and uncoated tool materials were

Maximum composition of elements	wt%
C	10.5
N	11.8
O	4.6
Al	23.6
Ti	41.1
V	0.5
Cr	0.4
Ba	13.7
W	1.9

Table 6.
EDS analysis results for coated AlTiN tools.

subjected to thermal and mechanical loads and could not be able to resist the wear during the interrupted cutting in the end milling process. The chip shape, segmented or continuous, decides the cutting temperature formation inciting to thermoplastic shear localization at the contact length, resulting in the diffusion process. The chip constituents and the rate of diffusion are controlled by cutting temperature. In the machining of titanium alloys, the machining parameters, particularly, cutting speed, influence the cutting temperature origination at the tool edge for initiating the diffusion process. The earlier researchers verified that cutting speeds generate high cutting temperature, a short contact length, a low shear angle and a high cutting pressure. Chip segmentation and tribological parameters—the physical medium—may be causing the coating delamination for both the coated tools while machining the titanium alloy. Since the thermal conductivities of the coating constituents are different, the heat flux q flows through the coating layer and penetrates the tool substrate. The reason behind the diffusion process at the tool substrate surface might be due to chemically instable Co binder elements. Adhesive surface between the coating layer and tool substrate surface was completely eliminated gradually by diffusion process as depicted in **Figures 7–12** and confirmed through EDS analysis.

3.2.2 EDS analysis

Adhesive, diffusion, abrasive and oxidation wear were the major means on the flank face. The elements observed on the cutting tool edge and workpiece indicate the diffusion process has taken place. From the EDS and SEM analyses, the existence of workpiece material constituents V, Al and Ti on the rake face wear land with built-up layer of cutting edge indicates diffusion might take place. Increasing cutting speed leads to the decrease in presence of V and Al at the tool cutting tool tip and it might be imaginable that Ti only sticks to the cutting tool edge. It has therefore been considered reasonable to suggest that the built-up layer was started through the sticking of Ti by different bonding actions, that is, directly proportional with temperature. Under very high speed cutting conditions, tool life depends directly on the formation of crater wear. Thin titanium oxide layer formation was observed on cutting edge of both the tools. In high-speed cutting conditions, cratering becomes so severe that the tool edge is weakened and eventually fracture which has been observed for the AlTiN and TiAlN tools at 110,000 rpm spindle speed, 0.1 mm depth of cut and 8 μm/tooth feed rate. At higher and lower

spindle speeds, existence of cobalt (Co) was very negligible. This indicates that Co diffusion might take place from the tool material constituents allowing it to wear easily. Through the EDS analysis, the amount of carbon presence indicates its transfer from cutting tool material into the workpiece material, that is, diffusion process might be taking place. This transfer of carbon reacts with titanium forming TiC layer which is continuous at higher speeds known as chemical wear process, leading to crater formation on tool material as observed by earlier researchers. The occurrence of crater wear might be due to chip-tool contact stresses generation, depleting the C and Co from cutting tool. An adherent layer of TiC formation exists on the cutting edge due to the chemical reaction between the titanium workpiece and the cutting tool material. Formation of oxycarbides on the surface indicates the existence of oxygen. Earlier researchers suggested this existence by Auger spectroscopy Analysis. Researchers also suggested that TiC grains removal might be taking place from the cutting tool because of reduction in toughness as the diffusion process takes place. Replenishing of TiC grains on the tool surface will probably occur by obtaining C from WC grains [3, 12–17, 21–29, 32]. The presence of Mo, Ni, Br, Cr, Fe and V indicates the work material composition diffusivity to the tool tip. Sulphur (S), silicon (Si) and magnesium (Mg) act as protective layer or barrier for adhesive wear and prevent the welding and stiffening of the work material in the tool surface. Through EDS analysis, it can be predicted that coating delamination in the initial stages may be due to mechanical wear later on by chemical mechanisms.

4. Conclusions

Tool wear analysis of PVD-coated TiAlN and AlTiN and uncoated tungsten carbide tools in high-speed micro-end milling of alpha + beta Ti-6Al-4V ELI titanium alloy (Grade 23) was investigated by tool wear mechanisms formation using SEM and EDS analysis and cutting force analysis. If the spindle speed is maintained at constant rpm while increasing feed rate and depth of cut, then tool wear increases dramatically. By increasing spindle speed from 30,000 to 70,000 rpm while varying feed rate and depth of cut, then (i) tool wear remains constant for uncoated tools, (ii) tool wear increases for AlTiN-coated tools and (iii) tool wear remains constant for TiAlN-coated tools. By increasing spindle speed from 70,000 to 110,000 rpm while varying feed rate and depth of cut, then tool wear increases for all the tools. If coated TiAlN and coated AlTiN tools are compared, then TiAlN tools performed better for machining this alloy. Based on the investigations, it can be suggested that PVD-coated TiAlN tungsten carbide tools give better performance than PVD-coated AlTiN and uncoated tungsten carbide tools in HSMEM at 110,000 rpm when machining alpha + beta Ti-6Al-4V ELI titanium alloy (Grade 23). SEM and EDS analyses for the considered machining operating parameters indicate the built-up edge, built-up layer and craters appearing at rake face and flank face of the cutting edge representing the adhesive, diffusion, oxidation and abrasive wear phenomenon on the tool surfaces when machined on both titanium alloys. Based on the investigations, the tool and work material properties, feed rate, depth of cut and cutting speed influence the tool wear.

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Conflict of interest

I would like to undertake that the abovementioned manuscript has not been published elsewhere, accepted for publication elsewhere or under editorial review for publication elsewhere.

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