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Tool Life of Uncoated and Coated Inserts during Turning of Ti6Al4V-ELI under Dry and Minimum Quantity Lubrication Environments

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ABSTRACT

This paper mainly deals with the tool wear characteristics of uncoated cemented carbide insert and PVD AlTiN, PVD TiAlN coated carbide inserts during turning of Ti6Al4V-ELI (Extra Low Interstitial). To satisfy the sustainability conditions, the experiments have been conducted under dry and minimum quantity lubrication (MQL) environment. To enhance the effectiveness of MQL, palm oil has been used as the cutting fluid. The same machining parameters are employed for all the cutting tool inserts in dry and MQL environments to understand the machining characteristics better. It was found that cutting speed greatly influences average flank wear. Tool life of PVD TiAlN coated tool is more in both MQL, and dry environments as compared to uncoated cemented carbide insert and PVD AlTiN coated insert. Using palm oil under the MQL environment has produced better results while turning by PVD TiAlN insert. The characteristics like good cooling and lubrication provided significantly less average flank wear during machining of Ti6Al4V-ELI under the MQLenvironment.

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NOMENCLATURE

Vc	Cutting Speed (m/min)	f	Feed (mm/rev)

1. INTRODUCTION

Titanium-based alloys are observed as the most significant materials in the aerospace and biomedical sectors. Titanium alloys cover around 30% of the material in an aerospace engine [1]. Due to this, it is also known as aerospace alloys. Titanium alloys are extensively used in steam turbine blades, superconductors, missiles, marine services, electronic gadgets, biomedical instruments, sports equipment due to their excellent strength and corrosion resistance properties. The high strength-to-weight ratio is one of the reasons for the popularity of these alloys among the numerous sectors. Titanium-based alloys possess high corrosion resistance, hot hardness, and wear resistance [2]. Even though many favourable properties of titanium alloys are still very difficult to machine due to their inherent properties such as high strength and hardness at elevated temperature, low thermal conductivity, low modulus of elasticity, self-induced chatter, work hardening behaviour, and chemical reactivity with various materials at elevated temperatures [3]. Various literature has commented on the poor machining behaviour of titanium alloys. In this concern, Ayed et al. [4] performed machining of titanium alloy Ti17 with uncoated tungsten carbide insert under diverse machining environments. Adhesion wear, abrasion wear, notch wear, and plastic deformation were found to be the main wear mechanism during the machining of Ti17. Bordin et al. [5] studied the tool wear of coated carbide insert observed by adhesive wear mechanism during machining of Ti6Al4V under dry and cryogenic

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environments. Klocke et al. [6] conducted machining of a gamma titanium aluminide alloy with an uncoated carbide insert under dry and MQL environments. Due to the absence of cutting fluid in a dry condition, abrasive wear was the leading wear mechanism. Deng et al. [7] and Pramanik et al. [8] studied diffusion wear during machining titanium alloy Ti6Al4V in a dry environment with WC-Co carbide tools. The results explored that W and Co elements did not significantly penetrate the titanium alloy Ti6Al4V at 400 °C, W and CO diffused into the titanium alloy Ti6Al4V. Armendia et al. [9] studied the machinabilities of Ti54M and Ti6Al4V with an uncoated WC-Co insert. They investigated that adhesion of work material in the form of a built-up edge appeared in all the cutting tools. Chetan et al. [10] observed less flank wear at a higher cutting speed due to the wettability behaviour of Ti6Al4V in the MQL environment. Fan et al. [11] investigated that diffusion, adhesion, and oxidation occurs at the chip-tool interface and accelerates their occurrence with increased cutting speed. Khatri et al. [12] found that abrasion wear was the most dominating tool wear mechanism during machining of Titanium alloy in dry and MQL environments. Guzanova et al. [13] explored that a coating made of powder with a low particle size belonging to the nanopowder coatings has a higher hardness, wear-resistance and almost the same corrosion resistance compared to the coating made up of large particle size. Brezinova et al. [14] found that green carbides coating is an environmentally more friendly replacement for coatings containing CO and Ni without reducing the performance of the coating.

Due to the advances in materials, investigators have now moved their attention to studying the machining behaviour of Ti6Al4V-ELI. It is evident from the available literature, and the author's perception that no systematic study has been conducted to analyze the tool flank wear and tool life of uncoated cemented carbide insert, PVD AlTiN, and PVD TiAlN coated insert during the turning of Ti6Al4V-ELI in dry and MQL environments. The extensive study about the tool life and tool wear during turning Ti6Al4V-ELI with uncoated cemented carbide insert, PVD AlTiN, and PVD TiAlN coated inserts under dry and MQL environments are still not available in the literature. Consequently, the key goal of this study is to find the tool life of uncoated cemented carbide insert, PVD AlTiN, and PVD TiAlN coated inserts in dry and MQL environments is a novelty work. Henceforth, the tool life of uncoated cemented carbide insert, PVD AlTiN, and PVD TiAlN coated inserts during machining Ti6Al4V-ELI in dry and MQL environment is quite innovative.

A comparative study of the machining of Ti6Al4V-ELI with uncoated cemented carbide insert, PVD AlTiN, and PVD TiAlN coated inserts will not only advantage in collecting more data concerning the tool wear characteristics but also help extend the research outputs from uncoated and PVD coated inserts. Moreover, the vegetable oil under the MQL environment during machining Ti6Al4V-With uncoated cemented carbide insert, PVD AlTiN, and PVD TiAlN coated inserts will be significant from economic and environmental aspects.

In the present study, machining of Ti6Al4V-ELI has been carried out under a dry and MQL environment. The cemented carbide uncoated insert, PVD AlTiN, and PVD TiAlN coated inserts have been selected based on the literature review and tool manufacturers' catalogue.

2. EXPERIMENTAL PROCEDURES

2. 1. Workpiece Material The workpiece material (220 mm length and 90 mm diameter) used during the turning process was in the form of a cylindrical bar of titanium alloy Ti6Al4V-ELI. The composition of the Ti6Al4V-ELI (in wt. %) is summarized in Table 1.

The microstructure of a workpiece consisted of an elongated alpha phase surrounded by fine, dark etching of the beta matrix. Ti6Al4V-ELI offers high strength and depth hardenability (32 HRC). The yield strength and ultimate tensile strength of Ti6Al4V-ELI are 795 MPa and 860 MPa, respectively. The modulus of elasticity is 114 GPa. The microstructure of Ti6Al4V- ELI is shown in Figure 1.

The microstructure of Ti6Al4V-ELI shows acicular alpha and aged beta. Alpha platelets at the prior beta grain boundaries. $HF+HNO_3+H_2O$ etchant was used.

2. 2. Cutting Tool A cutting tool inserts with ISO designation CNMG 120408FF KC5010 PVD AlTiN and

TABLE 1. Chemical composition of Ti6Al4V ELI

Composition	C	Si	Fe	Al	N
Wt %	0.08	0.03	0.22	6.1	0.006
Composition	V	S	O	H	Ti
Wt %	3.8	0.003	0.12	0.003	Balance

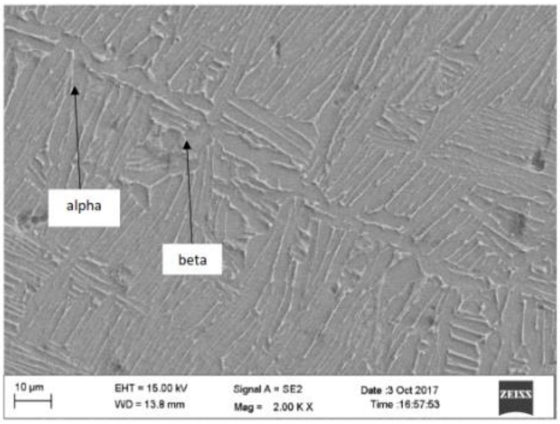
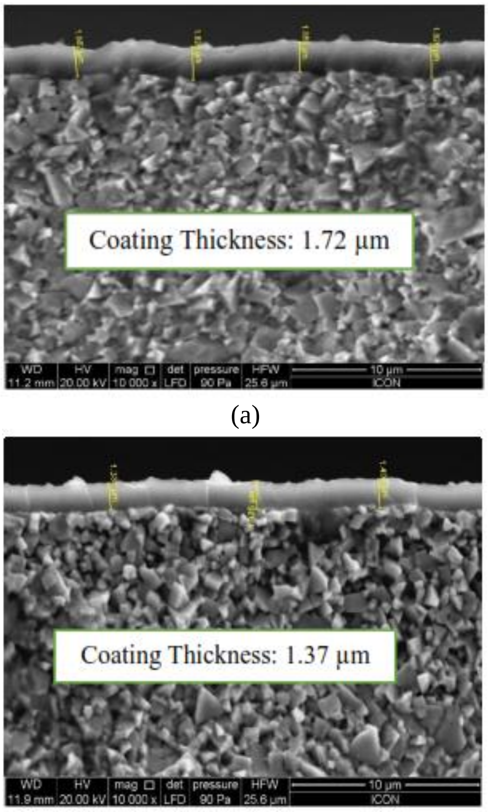


Figure 1. Microstructure of Ti6Al4V ELI

CNMG 120408MS K313 WC/Co uncoated insert Kennametal make CNMG 120408 SF 1105 Sandvik make, we selected for turning of Ti6Al4V-ELI. During experimentation PCLNL 2525 M12 tool holder was used.

The machining performance of the coated tool depends on the quality of both the substrate and the coating. Hence, it is imperative to characterize the selected cutting inserts. It may be noted that the characterization helps in a better understanding of the performance of the coated tool. The uncoated insert was characterized using Scanning Electron Microscopy (SEM). Figure 2 shows the EDAX profile and microstructure of the K313 uncoated cemented carbide insert observed under SEM. SEM image shows a uniform distribution of fine and medium grains. Microstructure and grain size are the most important factors, which govern the properties.

Figure 3 shows a fractured cross-section indicating the coating thickness of the PVD AlTiN and PVD TiAlN coated tools observed under a scanning electron microscope. The average coating thickness is 1.72 µm, and 1.37 µm of PVD AlTiN and PVD TiAlN coated tool, respectively.

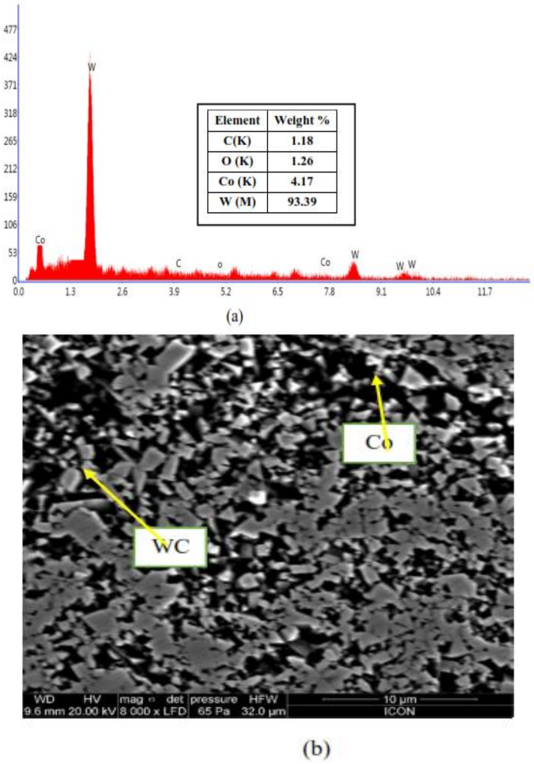


(a)

(b)

Figure 3. Coating Thickness of (a) PVD AlTiN (b) PVD TiAlN Coated Tool

2. 3. MQL Setup Minimum quantity lubrication helps as the substitute for flood cooling by reducing the volume of cutting fluid used during the machining process. In recent years, numerous methods have been developed to control the cutting temperature and increase the cooling process's overall effectiveness during the machining process. Machining in a dry environment is one of the techniques introduced as a new approach to decrease the environmental pollution. Cutting fluids are not supplied during the machining in a dry environment, but this method cannot be applied in all machining processes due to some constraints. All the materials cannot be machined without cutting fluids, and machining in a dry environment reduces tool life and affects the finishing process due to high heat generation. The flood coolant method has been used widely since cutting fluid was introduced in the machining industry. Cutting fluid is delivered excessively to cool and lubricate the cutting tool, and the workpiece subsequently reduces the heat generated at the chip-tool interface. The fast growth in the machine tool industry and the increasing awareness of environmental and health issues lead to near dry machining [15]. In the MQL method, a small amount of cutting fluid is carried by air-jet directly to the cutting zone leading to a decrease in cutting temperature. The photographic view of the experimental setup is shown in Figure 4. The block diagram of the MQL setup is illustrated in Figure 5. The conditions under which MQL is carried out are listed in Table 2.



Element	Weight %
C(K)	1.18
O (K)	1.26
Co (K)	4.17
W (M)	93.39

(a)

(b)

Figure 2. (a) EDAX Profile (b) SEM Micrograph of K313 Uncoated Cutting Tool

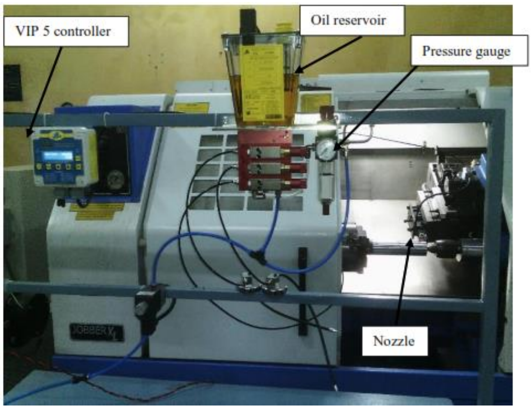


Figure 4. Photographic View of the Experimental Setup

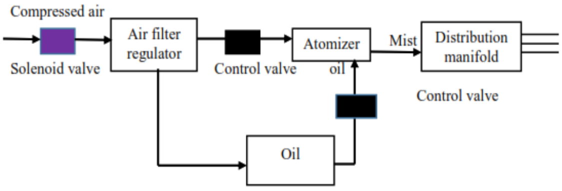


Figure 5. Block Diagram of MQL Setup

TABLE 2. Conditions of MQL System

Cutting Fluid	Palm Oil
MQL Flow Rate	100 ml/h
Air Pressure	5 bar
MQL Nozzle Distance form Contact Zone	20 mm

Working of the MQL setup is as follows:

- Compressed air with a typical air pressure of 5 bars is supplied into the air filter via a solenoid valve.
- The air filter removes any impurities or contaminations that may come along with the supplied air to keep the equipment clean and dirt-free.
- Meanwhile, cutting fluid is supplied to the mixing chamber from the oil reservoir via an oil control valve. The oil control valve is used to control the flow rate of oil to be supplied.
- In the mixing chamber, the compressed air from the filter via an air control valve and the cutting fluid gets mixed to form an aerosol known as oil mist.
- Oil mist is supplied to the machining zone through a nozzle having a very small hole (< 2mm).

2. 4. Measuring Equipment

- Dynamometer and charge amplifier: Kistler piezoelectric dynamometer (model-9257B) was used to measure the cutting forces in all three directions. The charge produced at the dynamometer was amplified using a charge amplifier (Kistler model-5019 B 130). The amplified signal was further processed with the help of Kistler Dynoware software.
- SEM and EDAX: FEI Quanta 200 Scanning Electron Microscope (SEM) was employed to take the worn-out tool's images at higher magnification. This SEM system can easily magnify the image from 5X to 10 X. It was used for elemental analysis work and tool material, measurement of coating thickness of PVD AlTiN and PVD TiAlN inserts, the microstructure of work material.

2. 5. Machining Parameters

The machining experiments were conducted on an ACE CNC LATHE JOBBER XL, which FANUC Oi Mate-TC as a controller. The turning process parameter values were designed during the experiments using the experiment's full factorial design. Three levels of cutting speed set the cutting parameters were 80, 125, and 170 m/min, while the three levels of feed were 0.08, 0.15, and 0.2 mm/rev. During the machining process, the depth of cut of 0.5 mm was kept constant. The machining experiments were carried out in a dry and MQL environment. The randomization concept was incorporated to select a sequence of machining parameters. The material was removed to avoid undesirable errors in turning tests. Before machining tests, a thin layer from work material was removed by turning process to remove out of roundness produced due to the earlier operations. A new cutting edge was used for each experiment.

3. RESULTS AND DISCUSSION

3. 1. Tool Wear

One of the primary purposes of utilizing cutting fluid in machining is to restrict tool wear and thus increase tool life by minimizing friction, temperature, and cutting forces. Therefore, the study of tool wear is significant for justifying the quantity of cutting fluid used. It is particularly so because cutting fluid has an adverse impact on the operator and the environment in general. Therefore, a detailed study has been undertaken to investigate tool wear under dry machining and MQL using an uncoated cemented carbide insert, PVD AlTiN, and PVD TiAlN single layer coated tool. Tool wear starts at a relatively faster rate due to break-in wear caused by attrition and microchipping at the sharp cutting edges. In the present investigation with the tool, work material, and the machining conditions undertaken, the tool failure modes were mostly gradual wear. In MQL, palm oil and air mixture were sprayed over the tool rake face, as shown in Figure 6.

Flank wear with cutting conditions of uncoated, PVD AlTiN, and PVD TiAlN cutting tool in a dry environment has been illustrated in Figures 7 and 8.

Excellent anti-friction property and wear resistance in combination with the superior thermal stability of TiAlN coating are responsible for the outstanding performance

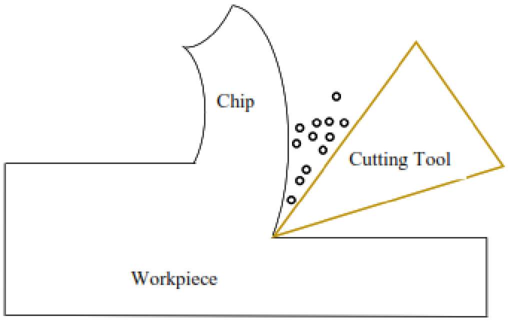


Figure 6. Schematic Diagram of MQL Mechanism at Tool-Work Interface

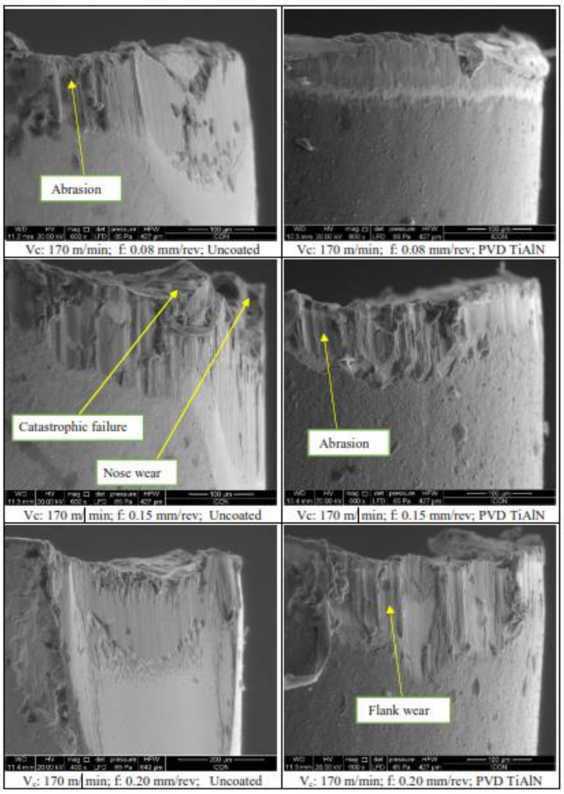


Figure 7. SEM images of tool wear pattern after turning of Ti6Al4V-ELI by using uncoated and PVD TiAlN insert in a dry environment (Turning length = 100 mm)

of PVD coated tool even during machining at such high cutting speed (170 m/min).

Average tool flank wear increases with cutting speed and feed for all the cutting tool inserts. However, cutting speed has a prominent effect on flank wear than feed rate. The PVD TiAlN cutting tool insert is the best for different cutting conditions in terms of low flank wear. The heat generated during cutting is less at low cutting speed and feed rate. As a result, PVD TiAlN coated tool withstands the temperature without affecting the tool geometry showing minimum wear.

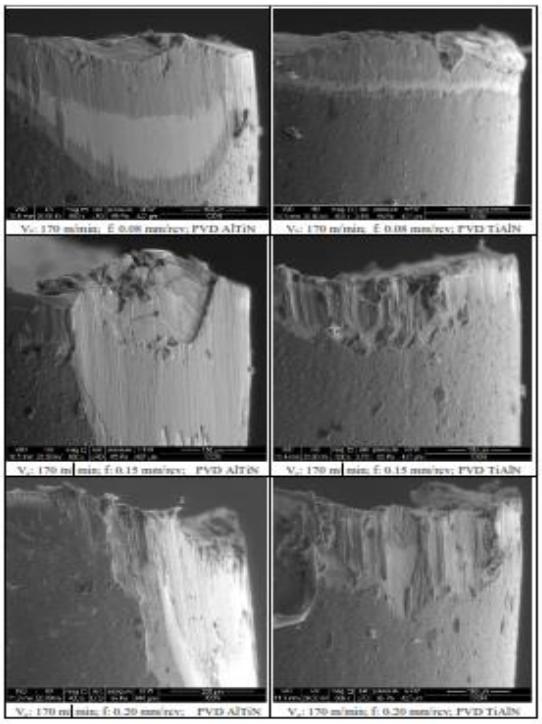


Figure 8. SEM images of tool wear pattern after turning of Ti6Al4V-ELI by using PVD AlTiN and PVD TiAlN insert in a dry environment (Turning length = 100 mm)

The wear rate of PVD AlTiN cutting tool insert is high compared to PVD TiAlN cutting tool insert at all cutting conditions, especially at high cutting speed and feed rate. High “Al” content in the PVD AlTiN tool cannot present better anti-wear properties than PVD TiAlN insert. High “Al” content in PVD AlTiN coating increased the chemical reactivity, which caused severe adhesive wear. Also, oxides of aluminium can increase the brittleness of the layer. Abrasive wear, adhesion wear, oxidation, and brittle failure were the main wear mechanism of the PVD AlTiN cutting tool insert.

3. 2. Tool Life

Figures 9 and 10 show the progression of average flank wear plotted against the duration of machining in a dry and MQL environment. Figure 11 shows the tool life of uncoated, PVD AlTiN, and PVD TiAlN coated tools in dry and MQL environments. The SEM images of growth of flank wear of uncoated, PVD AlTiN, and PVD TiAlN tools are shown in Figures 12 through 17, respectively.

The development of flank wear is evaluated in respect of machining time. Figures 9 and 10 show the average principal flank wear progression at the tool edge that encountered the cutting forces, contact stresses, temperature, and friction in a dry and MQL environment. The plots are constructed with the progression of machining time while the cutting speed, feed, and depth of cut were kept constant at 125 m/min; 0.08 mm/rev, and

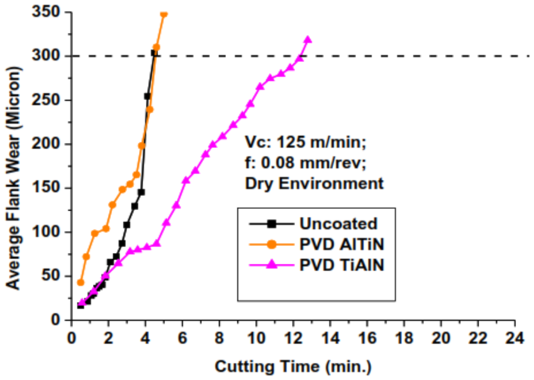


Figure 9. Progression of Average Flank Wear vs. Duration of Machining in a Dry Environment

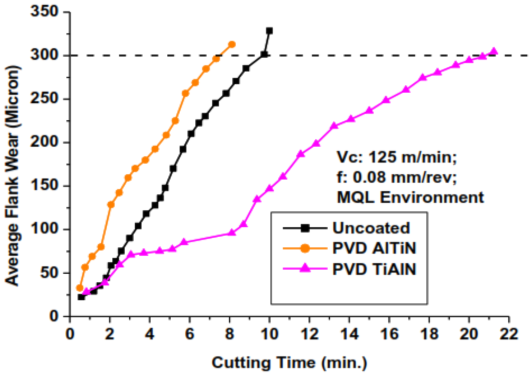


Figure 10. Progression of Average Flank Wear vs. Duration of Machining in MQL Environment

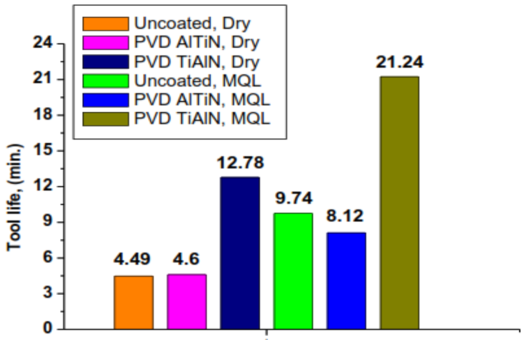


Figure 11. Tool life of Uncoated, PVD AlTiN and PVD TiAlN Coated Tool in dry and MQL Environment

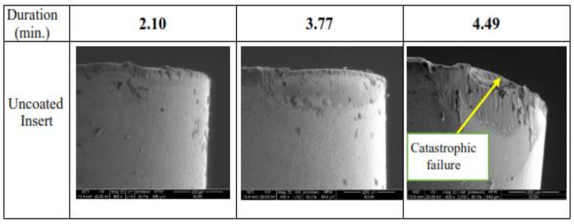


Figure 12. SEM images showing growth of flank wear of uncoated insert at cutting speed of 125 m/min, feed 0.08 mm/rev, and depth of cut 0.5 mm in a dry environment

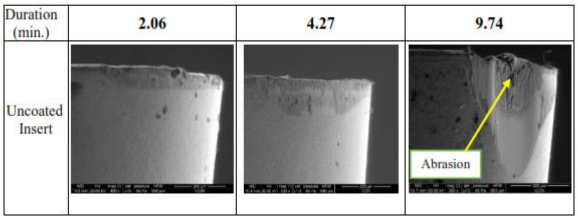


Figure 13. SEM images showing growth of flank wear of uncoated insert at cutting speed of 125 m/min, feed 0.08 mm/rev, and depth of cut 0.5 mm in MQL environment

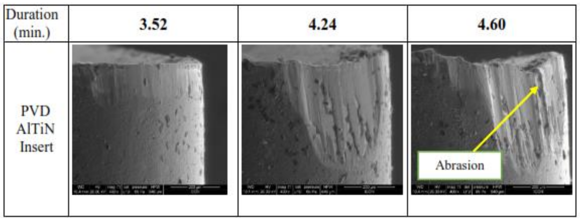


Figure 14. SEM images showing growth of flank wear of PVD AlTiN insert at cutting speed of 125 m/min, feed 0.08 mm/rev, and depth of cut 0.5 mm in a dry environment

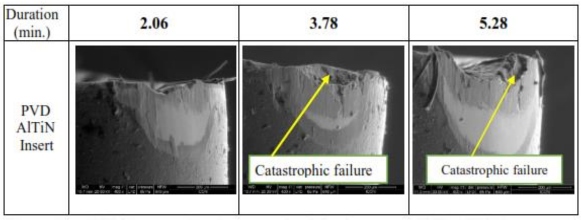


Figure 15. SEM images showing growth of flank wear of PVD AlTiN insert at cutting speed of 125 m/min, feed 0.08 mm/rev and depth of cut 0.5 mm in MQL environment

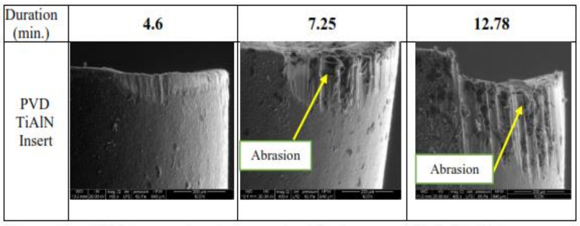


Figure 16. SEM images showing growth of flank wear of PVD TiAlN insert at cutting speed of 125 m/min, feed 0.08 mm/rev, and depth of cut 0.5 mm in a dry environment

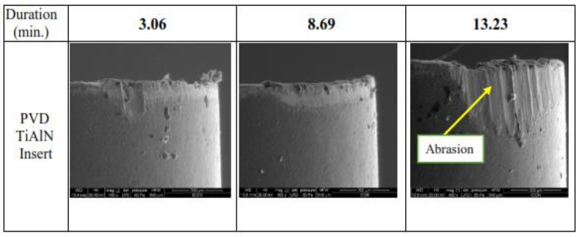


Figure 17. SEM images showing growth of flank wear of PVD TiAlN insert at cutting speed of 125 m/min, feed 0.08 mm/rev, and depth of cut 0.5 mm in MQL environment

0.5 mm, respectively. From Figures 9, it is observed that PVD TiAlN insert showed high tool life, the tool life of PVD AlTiN insert showed slightly more than tool life of uncoated tool in a dry environment at cutting speed 125 m/min, feed rate 0.08 mm/rev and depth of cut 0.5 mm. Also, it is observed that PVD TiAlN insert showed high tool life, the uncoated tool showed intermediated tool life, and PVD AlTiN insert exhibited low tool life. High “Al” content in PVD AlTiN coating increased the chemical reactivity, which aroused severe adhesive wear. Brittleness of the PVD AlTiN coating increases because of the oxide of aluminium. Adhesive wear, oxidation, abrasive wear, and brittle failure are the main wear mechanisms of the PVD AlTiN insert. The application of MQL effectively controls plastic deformation and thus promotes tool life [16]. It can be seen from Figure 10 that the average flank wear, particularly its rate of growth, decreased with MQL by palm oil. The reason behind the decrease in average flank wear observed might reasonably be attributed to a reduction in cutting temperature by MQL, which helped in reducing abrasion wear by retaining tool hardness as well as adhesion and diffusion types of wear which are highly sensitive to cutting temperature. Because of such a reduction in the growth rate of flank wear, the tool life is more in the case of the MQL environment than a dry one [17]. Many abrasion marks were observed on the cutting tool during machining in a dry environment due to a lack of lubrication and coolant. The vegetable oil in the MQL environment formed a lubrication film over the cutting tool and thus reduced the interaction of the workpiece and cutting insert [18]. Continuous adhesion and shearing-off built-up edge from the nose of the tool in a dry environment [19]. Catastrophic tool failure in dry and MQL environment at extreme cutting condition. The tool fracture and abrasion grooves were the major cause of tool wear in both dry and MQL environments. Tool flank wear is a significant criterion to judge the machinability of material because it is directly related to the dimensional accuracy and surface roughness [20].

3. 3. Cutting Force

With an increase in cutting speed from 80 to 170 m/min, the cutting force increased from 104 N to 282 N, which contradicts the results mentioned by Fang [20]. As cutting speed increases cutting force increases due to strain gradient induced material strengthening effects. This makes it challenging to increase cutting speed when machining Ti6Al4V-ELI. With an increase in the feed from 0.08 to 0.20 mm/rev, the cutting force was found to increase from 104 N to 282 N. An increase in feed increases cutting force due to an increase in the area of undeformed chip cross-section, which increases the friction between the cutting edge and workpiece. An increase in the feed also increases the chip load, which causes excessive cutting force. Also, the increased deformation due to the increased feed in turning requires a higher cutting force. The cutting force increased from 104 N to 248 N while turning Ti6Al4V-ELI in the MQL environment. The cutting force increased from 128 N to 282 N in a dry environment. Increasing the friction between the cutting edge and workpiece while turning Ti6Al4V-ELI in a dry environment result in more cutting force than the MQL environment. PVD TiAlN coated tool exhibited lower cutting force because coating increases the lubricity and reduces the affinity to the workpiece material and low coefficient of friction of the PVD TiAlN insert.

4. CONCLUSIONS

This research article discussed the tool wear characteristics of uncoated cemented carbide insert, PVD AlTiN, and PVD TiAlN inserts during machining of Ti6Al4V-ELI in dry and MQL environments. The following conclusions can be drawn from the present work:

- The average flank wear increased with cutting speed and feed due to the rise in plastic deformation and temperature. Cutting speed has a dominating effect on tool flank wear.
- Adhesion and cutting-edge chipping were more dominant wear mechanisms for uncoated tools.
- PVD TiAlN tool insert showed low tool flank wear because of good adhesion strength and high thermal conductivity. PVD TiAlN tool exhibited longer tool life than uncoated and PVD AlTiN inserts.
- Flank wear is less in the MQL environment due to the excellent wettability behaviour of Ti6Al4V-ELI. MQL has significantly reduced tool flank wear compared to dry machining due to the effective cooling and lubrication.
- Better penetration of palm oil during machining of Ti6Al4V-ELI provided less crater wear due to less tool-chip contact length.
- Outstanding improvement in resistance to tool wear indicative of superior machinability was consistently obtained with PVD TiAlN coated tool in MQL environment.
- Surface finish enhanced predominantly due to reduction of damage and wear at the tool tip by applying MQL.
- Good adhesion strength, high wear resistance of PVD TiAlN coated tool associated with superior tribological features resulted in increased tool life.
- The tool wear mechanism of the PVD TiAlN coated tool was a combination of abrasive wear, oxidation, and micro-grooves. PVD TiAlN coated tool possesses the lowest wear rate because of the adding of ‘Al.’
- PVD AlTiN coating increased the chemical reactivity because of high ‘Al’ content in PVD AlTiN coated tool results in poor performance compared to PVD TiAlN insert.

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Persian Abstract

چکیده

این مقاله عمدتاً به ویژگی‌های سایش ابزار درج کاربید سیمانی بدون پوشش و درج‌های کاربید پوشش‌داده‌شده (PVD AlTiN، PVD TiAlN) در هنگام چرخش Ti6Al4V-ELI بینابینی بسیار کم می‌پردازد. برای برآوردن شرایط پایداری، آزمایش‌ها در محیط خشک و حداقل مقدار روانکاری (MQL) انجام شده است. برای افزایش اثربخشی MQL، روغن نخل به عنوان مایع برش استفاده شده است. پارامترهای ماشینکاری یکسان برای همه درج‌های ابزار برش در محیط‌های خشک و MQL به کار گرفته می‌شود تا ویژگی‌های ماشینکاری را بهتر درک کنید. مشخص شد که سرعت برش تا حد زیادی بر سایش متوسط پهلو تأثیر می گذارد. عمر ابزار ابزار پوشش داده شده PVD TiAlN در هر دو محیط MQL و خشک در مقایسه با درج کاربید سیمانی بدون پوشش و درج پوشش دار PVD AlTiN بیشتر است. استفاده از روغن نخل در محیط MQL نتایج بهتری را در حین چرخش توسط درج PVD TiAlN ایجاد کرده است. ویژگی‌هایی مانند خنک‌کاری و روان‌کاری خوب، به طور قابل‌توجهی متوسط سایش جانبی کمتری را در طول ماشینکاری Ti6Al4V-ELI تحت شرایط محیطی MQL ارائه می‌کنند.