



## Analysis of Microhardness after Turning Process of Ti6Al4V-ELI

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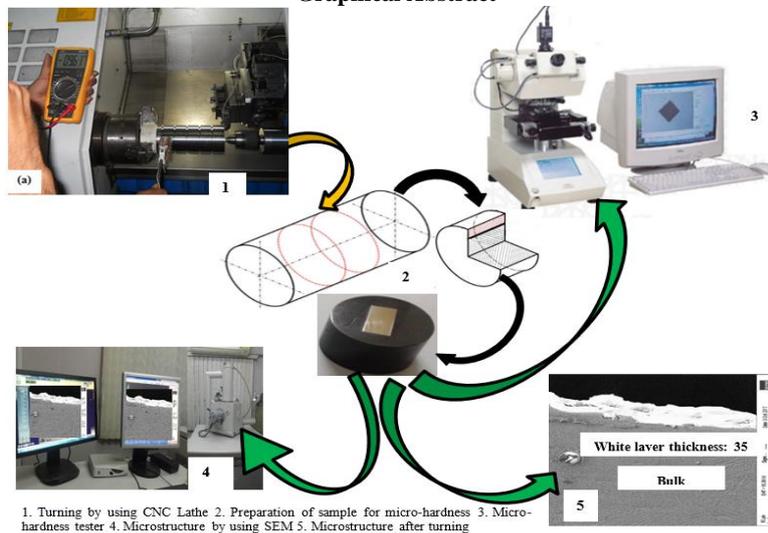
Machining Affected Zone

### ABSTRACT

This study investigated the effect of cutting parameters on the microhardness of Ti6Al4V ELI during dry turning using PVD AlTiN and TiAlN inserts. Addressing the challenge of balancing productivity with stringent surface integrity requirements, this research explored the influence of cutting speed (80, 125, and 170 m/min) and feed rate (0.08, 0.15, and 0.20 mm/rev) on subsurface microhardness. Vickers microhardness testing revealed a clear work hardening tendency, with the highest microhardness observed in the subsurface region. Increasing cutting speed correlated with increased microhardness, particularly when using PVD TiAlN inserts, indicating a greater degree of microstructural alteration. A thicker white layer was observed after turning with PVD AlTiN inserts compared to PVD TiAlN, potentially due to differences in friction coefficient. Maximum microhardness (398 HV<sub>0.05</sub>) was recorded at 125 m/min cutting speed and 0.20 mm/rev feed rate with PVD TiAlN. The machining affected zone (MAZ) extended to 200  $\mu$ m and 300  $\mu$ m below the surface for AlTiN and TiAlN inserts, respectively. These findings provide insights for optimizing machining processes to enhance both surface integrity and productivity in the manufacturing of Ti6Al4V ELI components.

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### Graphical Abstract



1. Turning by using CNC Lathe 2. Preparation of sample for micro-hardness 3. Micro-hardness tester 4. Microstructure by using SEM 5. Microstructure after turning

### NOMENCLATURE

V <sub>c</sub>	Cutting Speed (m/mni)	f	Feed (mm/rev)
HV <sub>0.05</sub>	Vickers hardness scale for load of 0.05 kgf	PVD	Physical Vapor Deposition

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## 1. INTRODUCTION

The product's surface integrity and work efficiency are greatly impacted by the machining parameters. High temperatures at the cutting zone lead to plastic deformation, chemical reactions at the tool-chip interface, and changes in the surface layer (1). Surface integrity investigates the situation of the surface layer and its effect on mechanical and functional properties of the machined component (2). Microhardness, roughness, surface layer, surface topography and chemical composition of work material are the most significant features of the surface integrity (3). Dry turning is the best technique to decrease the adverse effects of cutting fluids is to totally remove (4). A high pure grade of Ti-6Al-4V alloy is the outstanding Ti6Al4V ELI alloy. It has low carbon, iron, and oxygen. Because of its low modulus and good fatigue strength, it is used in biomedical applications like as bone fixation devices, joint replacements, surgical clips, and cryogenic vessels. Additionally, it is the preferred quality for aeronautical and marine applications. Ti6Al4V ELI is a difficult material to cut due to its high chemical reactivity, low modulus of elasticity, low heat conductivity, thermal plastic instability, and work hardening (5, 6). Surface integrity is a metric used to quantify the quality of machined surfaces. The metallurgical, mechanical, topological, and chemical states of a surface determine surface integrity. Fields including biomedicine, the electrical industry, and aerospace, surface integrity is important. Surface integrity is greatly influenced by machining conditions, tool material, tool shape, and tool coating; surface microhardness plays a key role in determining corrosion resistance and fatigue fracture initiation (7, 8). When TC17 titanium alloy is high-speed milled, surface hardness rises with increasing cutting speed (9). When machining in a dry environment, titanium alloys' high microhardness and poor machinability index cause premature tool wear (10). Surface and subsurface microhardness decreases when Ni-based super alloys are machined using coated inserts (11). Because of work hardening during machining of Ti alloys surface hardness is greater than the hardness of base metal (12). As cutting speed rises, microhardness rises 90  $\mu\text{m}$  below the machined surface (13). 50  $\mu\text{m}$  below the machined surface, the microhardness is 8% lower than the bulk material hardness. In the spectrum of machining parameters examined, the greatest microhardness value during the turning of titanium alloy is 394  $\text{HV}_{0.05}$  (14). As a cutting speed increases the microhardness increases at a constant feed rate. Microhardness increases when machining is done by the worn tool (15). Because of the work hardening effect, the microhardness at the machined surface is greater than the workpiece material's average hardness (16). Increasing the temperature while turning in a dry environment

prevents the increase of hardness of subsurface and surface (17). Microhardness increased during titanium alloy turning as the depth below the machined surface increased (18). As the depth of cut and feed rate increase, microhardness rises at surface as well as beneath the surface (19). As an increasing coolant pressure, hardening effect decreases (20). Microhardness rises beneath the machined surface (30  $\mu\text{m}$  to 100  $\mu\text{m}$ ) as a result of titanium alloy strain hardening due to plastic deformation during the machining process (21). During machining, mechanical forces and heat reactions cause a noticeable change in the microstructure of the machined surface (22). After machining at a high feed rate and cutting speed, a heavily plastic deformed layer was produced (23). In the turning of titanium alloy Ti6Al4V, the subsurface hardness is less than the bulk material about 200  $\mu\text{m}$  below the turned surface, but it is more than the bulk material up to 100  $\mu\text{m}$  below the turned surface (24). Near the machined surface of Inconel 718 during the turning process, the microhardness is 50% greater than the bulk hardness (25). As cutting speed and tool flank wear rise, so does the thickness of the white layer. Compared to bulk material, the white coating is brittle and hard (26). The main element affecting the noticeable change in the subsurface layer's microhardness was cutting speed (27-30). When the uncut chip thickness to cutting edge radius ratio falls, microhardness rises (28).

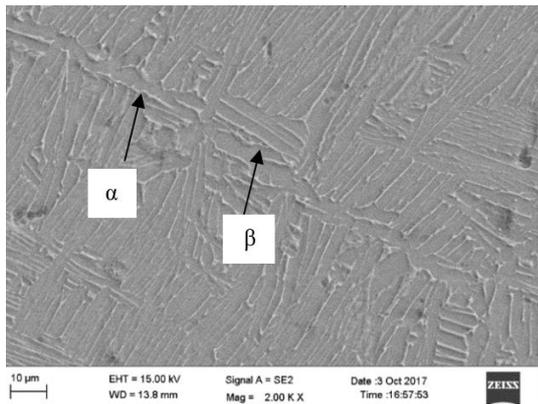
The literature survey conducted by the author reveals a need for systematic investigation into the microhardness of machined Ti6Al4V ELI.

Research challenges related to surface integrity after Ti6Al4V ELI turning employing PVD AlTiN and PVD TiAlN coated inserts are the primary objective of this study.

Primary goal of this investigation is to explore the performance of PVD coated AlTiN and TiAlN inserts at different machining parameters and investigate the impact of machining conditions on the microhardness of the turned surface after the turning of Ti6Al4V ELI in a dry environment.

## 2. MATERIALS AND METHOD

Workpiece material: Ti6Al4V extra low interstitial (ELI) bar with dimensions 210 mm length and 80 mm diameter was used for experimental work. The titanium alloy Ti6Al4V ELI has the following chemical compositions in %: Si: 0.03, C: 0.08, Al: 6.1, Fe: 0.22, N: 0.006, O: 0.12, S: 0.003, H: 0.003 and V: 3.8 with Ti being the remaining significant element. Ti6Al4V ELI has good fatigue strength, fracture toughness, and a high tensile strength. The microstructure of the titanium alloy Ti6Al4V ELI, which was examined using a scanning electron microscope, is depicted in Figure 1. The titanium



**Figure 1.** Microstructure of titanium alloy Ti6Al4V ELI

alloy Ti6Al4V ELI's microstructure exhibits aged beta and acicular alpha. The HF+HNO<sub>3</sub>+H<sub>2</sub>O etchant was used for the preparation of the sample prior to analysis of the microstructure.

- Cutting tools and cutting parameters: A rhombic shape PVD TiAlN and PVD AlTiN cutting tool inserts were used for the machining of titanium alloy Ti6Al4V ELI in dry environment.

ISO designation of PVD TiAlN is CNMG 120408-SF-1105 (Sandvik make) and ISO designation of PVD AlTiN is CNMG 120408-FF, KC 5010 (Kennametal make) on the basis of a tool manufacturer's catalogue and concluding remarks from the former exploration. A levels of turning process parameters are shown in Table 1.

- Tool holder: PCLNL 25 25 12 tool holder was used. Principal cutting edge angle 95°, back rake angle 13°, auxiliary cutting edge angle 5°.
  - CNC lathe : ACE CNC Lathe Jobber XL (FANUC controller) was used for machining with 5000 RPM.
- Microhardness measurement: Shimadzu's HMV-2T microhardness tester measures the machined surface's microhardness. Microhardness was measured using a diamond with a square base pyramid Vickers indenter, which had opposing faces at an angle of 136°. Fifty grams of load and fifteen seconds of dwell time were used to measure microhardness. The length of the two diagonals (horizontal and vertical) of the pyramid indentations was measured in order to calculate the microhardness at each

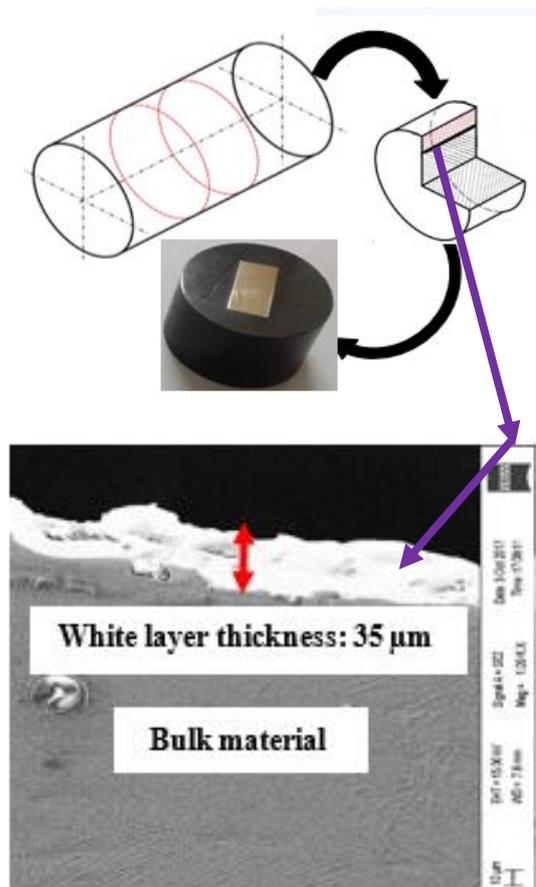
**TABLE 1.** Turning Process Parameter

Parameter	Level 1	Level 2	Level 3
Cutting Speed, Vc	80	125	170
Feed, mm/rev	0.08	0.15	0.20
Depth of Cut, a <sub>p</sub>	0.5 constant		
Tool	PVD TiAlN	PVD AlTiN	--
Environment	Dry		

location. For each sample, the average length of the diagonals under the turned surface was employed to improve the microhardness measurement's accuracy. Three distinct locations were chosen at an equal depth below the cutting surface in order to reduce the inaccuracies caused by measuring position. Graphical abstract shows Experimental procedure and Figure 2 shows the samples were prepared after turning of Ti6Al4V ELI work material for the microhardness measurement and analysis of microstructure. Wire EDM was used to cut the work material, and metallographic techniques were used to prepare the samples. Under the turned surface, the microhardness in the subsurface layer has been measured. The surface of the sample was prepared by polishing and grinding. The sample was treated with HF + HNO<sub>3</sub> + H<sub>2</sub>O etchant in order to view and analyse the microstructure under a scanning electron microscope. Measurements of microhardness were made at various points below the machined surface.

## 2. 1. Significance of Measurement of Machined Surface Microhardness

Since the product's surface integrity typically determines its primary



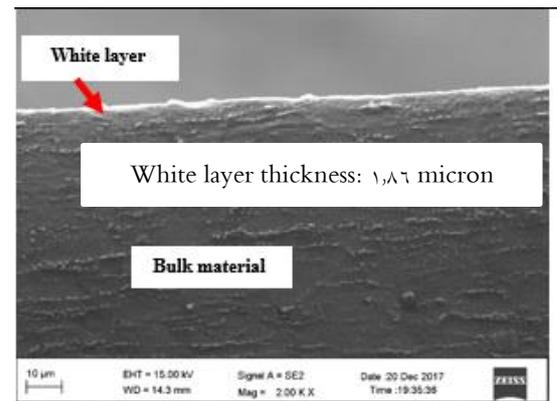
**Figure 2.** Technique of sample preparation for microhardness testing

performance, controlling the physical aspects of surface integrity is important during the machining process.

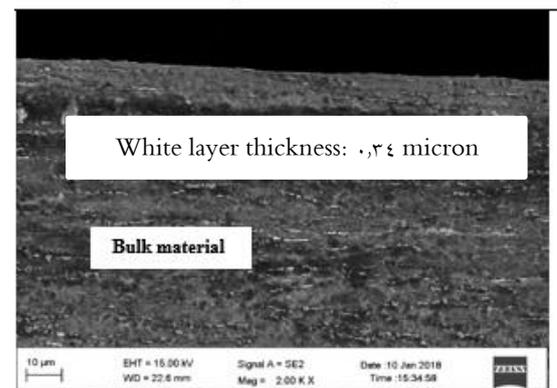
The main factors that influence of surface integrity are temperature at the tool-work interface, machining environment, tool shape, and turning process parameters. The main zone, or tool-work interface, is where heat is typically generated during the turning process. The subsurface layer is penetrated by the temperature from the machined surface, which significantly affects the surface integrity. One important consideration when analysing surface integrity is microhardness. The microhardness value of the machined component influences on its functional performance. A metallurgical change of the subsurface layer at multiple depths under the machined surface can be identified with the use of microhardness measurement. After machining, the machined surface's microhardness value is used to verify the impact of surface hardening. The machining affected zone (MAZ) were investigated using measurement of microhardness.

### 3. RESULTS AND DISCUSSION

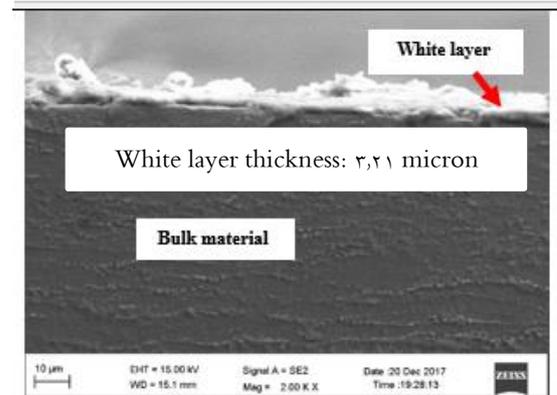
Measuring microhardness aided in separating the bulk material from the machining affected zone (MAZ). At a depth of roughly 500  $\mu\text{m}$  below the machined surface, the microhardness of the machining-affected zone gradually gets closer to bulk microhardness. The microhardness is found to be around 3% more than the bulk microhardness at a depth of about 10  $\mu\text{m}$  below the machined surface. The microhardness was higher near the surface and then reduced as the depth beneath the machined surface increased. Figure 3 shows the SEM images of microstructure of machined surface. White layer formation is a frequently observed phenomenon on Ti6Al4V ELI after machining, particularly in dry cutting conditions. This very thin layer on the workpiece surface often appears featureless or "white" under a scanning electron microscope after etching. The white layer's characteristic extremely fine-grained or even amorphous structure results from the severe plastic deformation and rapid heating/cooling cycles experienced during the cutting process. It is proposed that white layer formation occurs primarily through a mechanism of continuous dynamic recrystallization (CDRX) driven by intense plastic deformation. Beneath the white layer, a region of plastically deformed material is typically found, often manifesting as elongated grains, distorted grain boundaries, or even deformation twins. The extent of this deformation is influenced by cutting parameters such as cutting speed, feed, and depth of cut, as well as the tool geometry. It is revealed from Figure 3 a thicker white layer is observed after turning with PVD AlTiN insert, compared to PVD TiAlN insert, indicates a potential difference in friction coefficient between the two



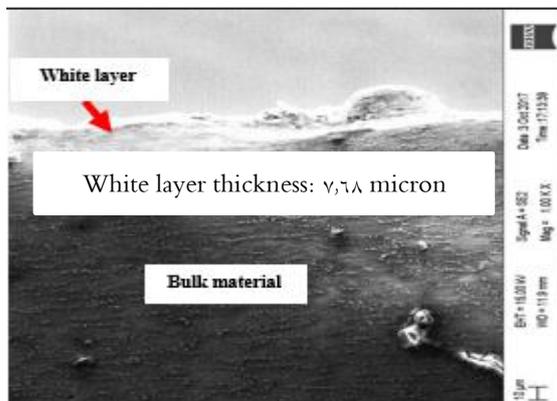
TiAlN insert; Vc: 80 m/min; f: 0.08 mm/rev



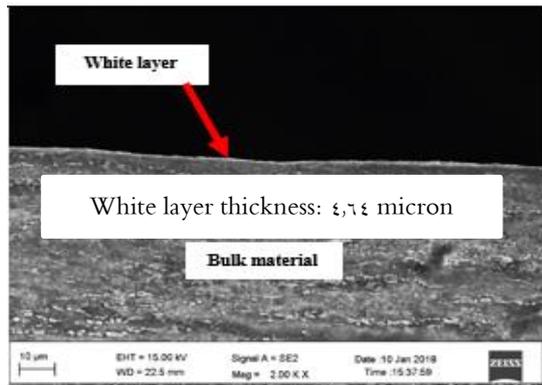
TiAlN insert; Vc: 125 m/min; f: 0.08 mm/rev



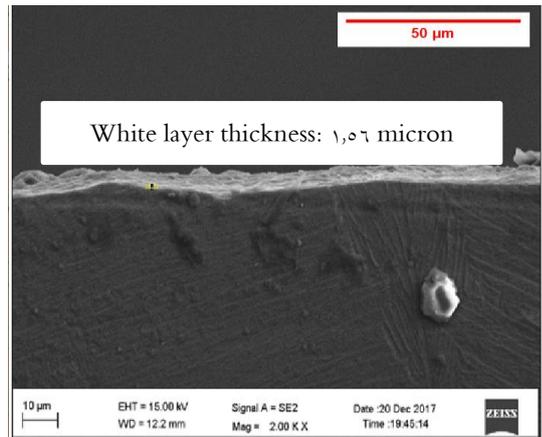
TiAlN insert; Vc: 170 m/min; f: 0.08 mm/rev



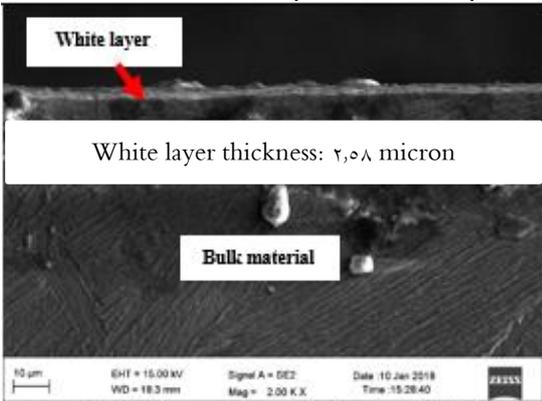
TiAlN insert; Vc: 170 m/min; f: 0.15 mm/rev



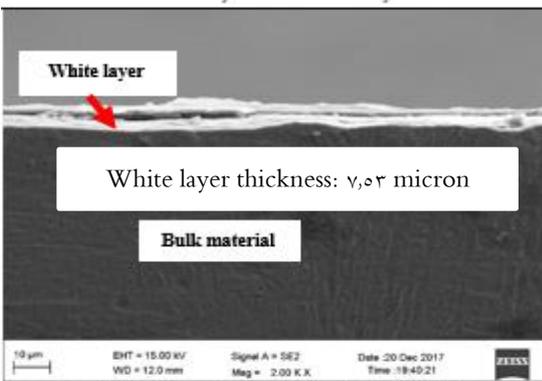
**TiAlN insert; Vc: 170 m/min; f: 0.2 mm/rev**



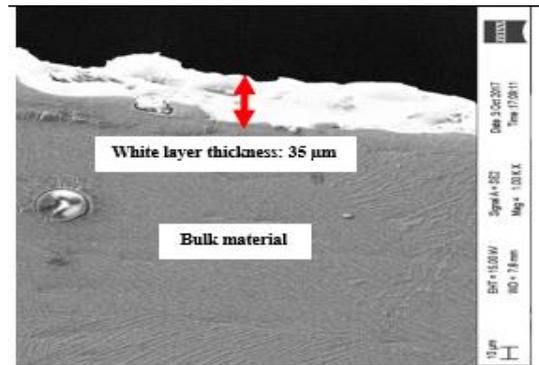
**AlTiN insert; Vc: 80 m/min, 0.08 mm/rev**



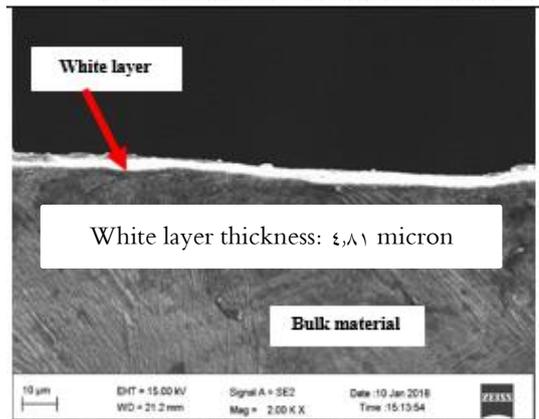
**AlTiN insert; Vc: 125 m/min; f: 0.08 mm/rev**



**AlTiN insert; Vc: 170 m/min; f: 0.08 mm/rev**



**AlTiN insert; Vc: 170 m/min; f: 0.15 mm/rev**



**AlTiN insert; Vc: 170 m/min; f: 0.2 mm/rev**

**Figure 3. SEM images of microstructure of the machined surface**

coatings. A higher friction coefficient with the AlTiN insert could lead to increased heat generation at the tool-workpiece interface, thereby exacerbating the conditions that favor white layer formation.

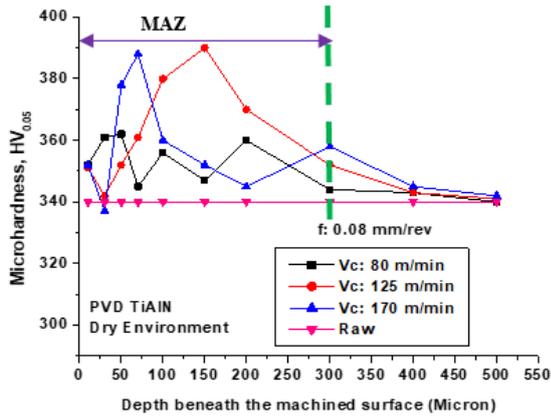
The important process variable that has the biggest impact on the amount of heat generated in the cutting area is cutting speed. Microhardness is one of the functional parameters that will be impacted by the heat that penetrates the work material's surface layer during turning. Figure 4 illustrates how cutting speed affects the microhardness of the turned surface after the turning of Ti6Al4V ELI with PVD coated TiAlN insert. Plots of microhardness values recorded up to 0.5 mm below the machined surface in a dry environment are shown in Figures 4 through 7. Higher micro-hardness values indicate a greater degree of work hardening. Therefore, the observed increase in micro-hardness with increasing cutting speed suggests a corresponding increase in the work hardening rate.

From Figure 4a it was observed that the effect of work hardening was very much dominant over the thermal softening. Figure 4 shows that hardening rate increases as cutting speed increases. At cutting speed of 170 m/min microhardness value 337 HV<sub>0.05</sub> was recorded and 342 HV<sub>0.05</sub> microhardness value recorded at 125 m/min at

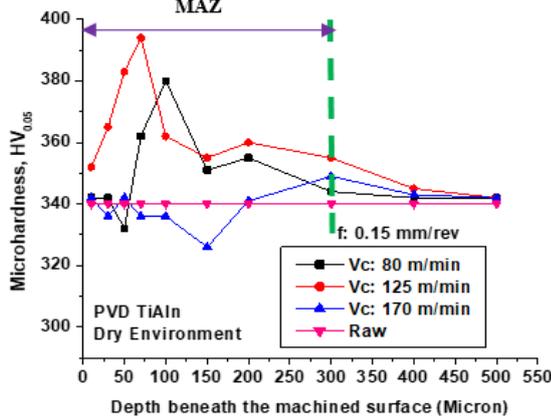
same depth, this softening effect is probably due to overaging due to high cutting temperature produced at the local surface.

From Figure 5b it is clear that the effect of work hardening is dominant. It is observed from the microhardness profiles that the pattern of microhardness

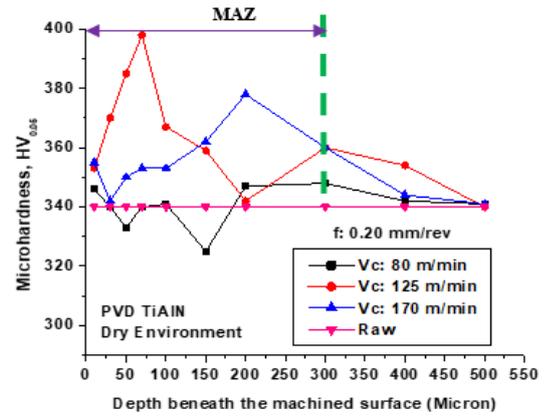
variation is almost similar for all the samples till 200 microns depth beneath the surface. The effect of feed rate on the microhardness of machined surface after turning of Ti6Al4V ELI with PVD TiAlN insert which are shown in Figure 5.



(a)

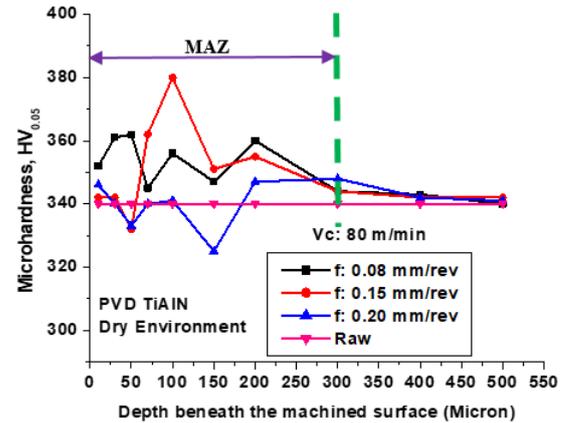


(b)

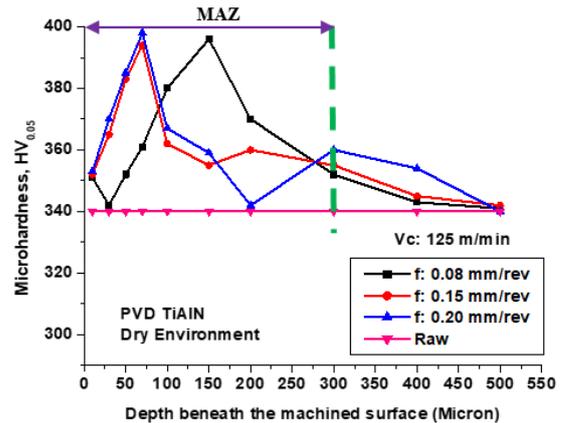


(c)

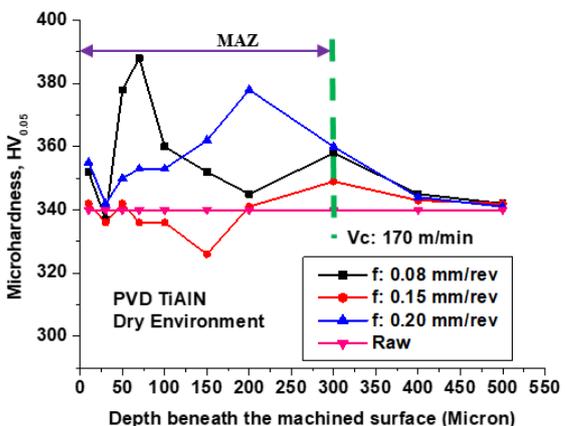
**Figure 4.** Effect of cutting speed on microhardness when machining by PVD TiAlN insert at constant feed rate (a) 0.08 mm/rev (b) 0.15 mm/rev (c) 0.20 mm/rev



(a)



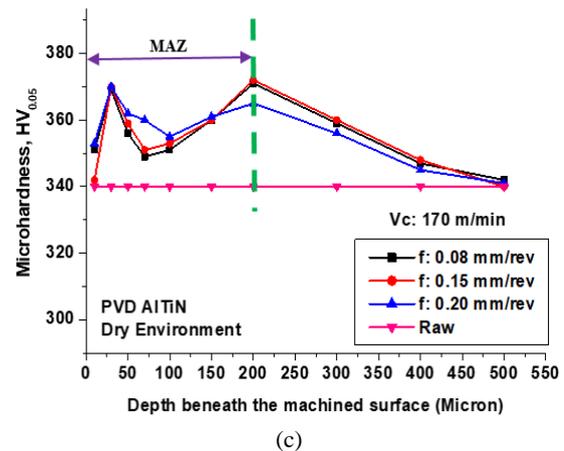
(b)



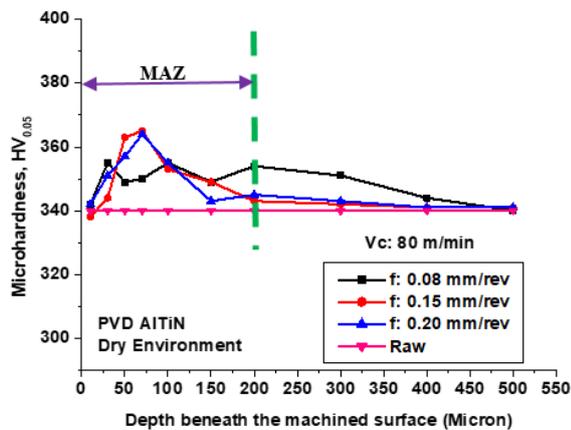
(c)

**Figure 5.** Effect of feed rate on microhardness when machining by PVD TiAlN insert at constant cutting speed (a) 80 m/min (b) 125 m/min (c) 170 m/min

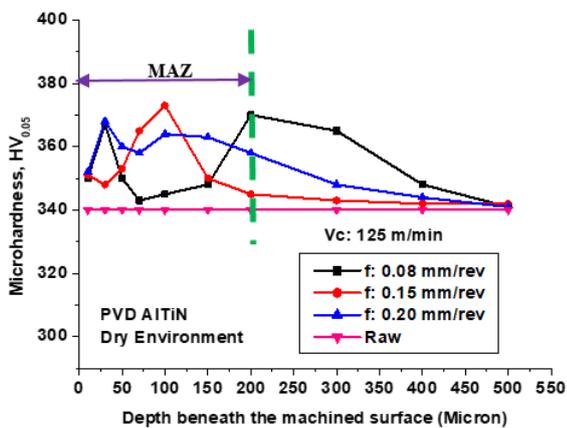
It is observed from Figure 6a that the hardening rate at 125 m/min and 170 m/min is higher than that of 80 m/min possibly because of higher cutting force involved at higher cutting speed. Highest microhardness value i.e. 369 HV<sub>0.05</sub> was recorded at 170 m/min cutting speed. It is observed from Figure 6b that the sudden increase in microhardness value and it is recorded from 342 to 370 HV<sub>0.05</sub> at 30 micron below the turned surface which clearly shows that beneath the machined surface work hardening of deformed layer. The effect of over aging is seen in between 30 to 70 micron. It is explored from Figure 6b the cutting speed is dominant factor in process work hardening. It is observed from Figure 6c that the hardening rate at cutting speed of 170 m/min was higher as compared to 80 and 125 m/min cutting speed. As the cutting speed increases, the rate of deformation and friction at the tool-workpiece interface increases, leading to more heat generation. As we increase cutting speed, the rate of plastic deformation in the workpiece surface layer also increases. This leads to greater work hardening, making the surface harder. The effect of cutting speed on the microhardness after turning of Ti6Al4V ELI with PVD coated AlTiN insert which are shown in Figure 6.



(c)  
**Figure 6.** Effect of cutting speed on microhardness when machining by PVD AlTiN insert at constant feed (a) 0.08 mm/rev (b) 0.15 mm/rev (c) 0.20 mm/rev



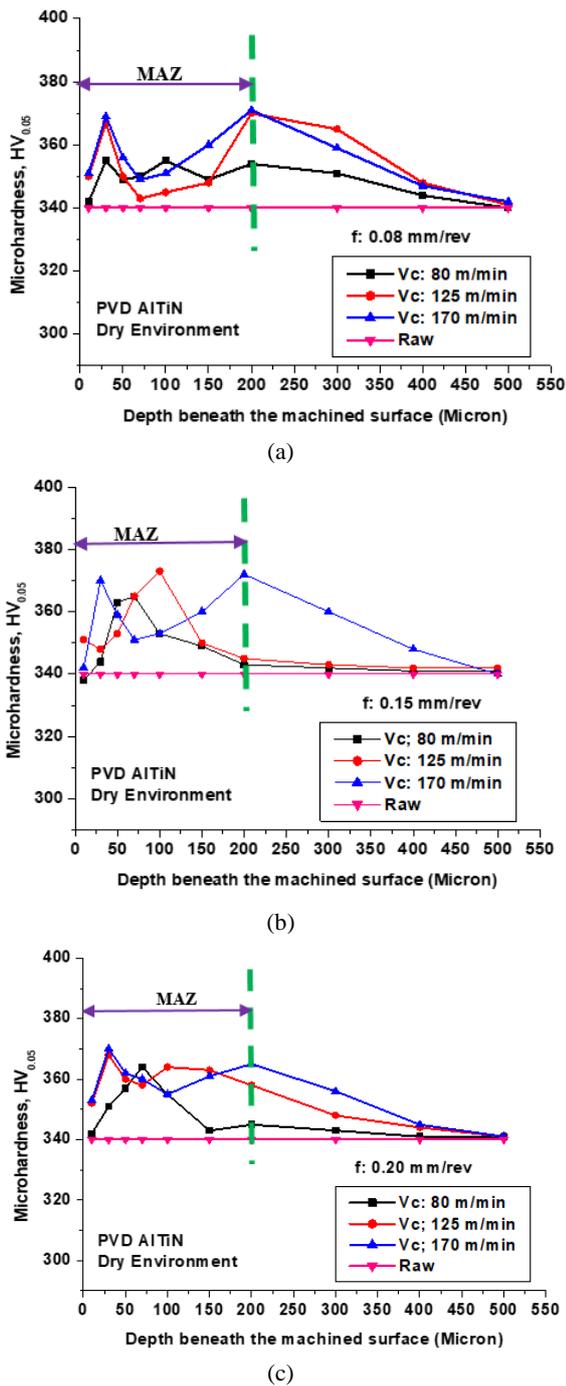
(a)



(b)

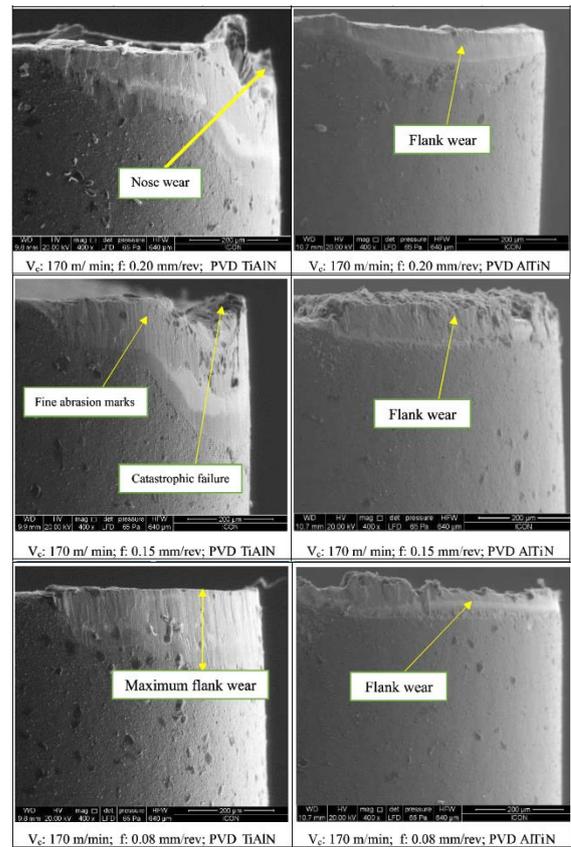
From Figure 7a it was observed that an aggressive increase in microhardness was recorded up to 70 microns for feed rates of 0.15 and 0.20 mm/rev. The fluctuating pattern of microhardness was recorded at feed rate of 0.08 mm/rev with 362 HV<sub>0.05</sub> as a highest microhardness value at 50 micron beneath the machined surface. Figure 7b shows that the effect of thermal softening shows that was observed in region between 70 to 100 microns, 343 HV<sub>0.05</sub> was the lowest value of microhardness recorded in this region. The thermal softening was caused by the overaging resulting from the higher cutting temperature (31). It has been noted that as cutting speed increases from 80 to 170 m/min, temperature rises (31). Consequently, the microhardness of the machined surface increases as a result of the strain hardening effect. The effect of feed rate on the microhardness after turning of Ti6Al4V ELI with PVD AlTiN insert which are shown in Figure 7. Maximum surface hardening has been observed to occur when the average flank wear increases with cutting speed. Microstructure is impacted by the flank wear. Scanning electron microscopy was used for to measure the flank wear. Tool wear pattern of PVD TiAlN and AlTiN insert by using SEM which is shown in Figure 8. Flank wear is a type of tool wear that occurs on the flank face of the cutting tool. Increased flank wear often indicates higher cutting temperatures. When flank wear increases with cutting speed, it suggests that the thermal softening effect is becoming more prominent. However, if maximum surface hardening is observed under these conditions, it means that the work hardening effect is still dominant, even though thermal softening is playing a role.

Since Ti6Al4V ELI has a low thermal conductivity, the temperature below the machined surface will be maintained. Using a PVD coated TiAlN insert in a dry condition and turning at a feed rate of 0.20 mm/rev and cutting speed of 125 m/min and, the highest



**Figure 7.** Effect of feed rate on microhardness when machining by PVD AlTiN insert at constant cutting speed (a) 80 m/min (b) 125 m/min (c) 170 m/min

microhardness measured value was 398 HV<sub>0.05</sub>. At 70 microns below the machined surface, where the microstructure was severely distorted, the highest value of microhardness was measured. The work hardening effect was the cause of the increase in the microhardness value.



**Figure 8.** Tool wear pattern of PVD TiAlN and PVD AlTiN insert at Vc: 170 m/min; f: 0.08 mm/rev, 0.15 mm/rev, 0.20 mm/rev in Dry environment

As the depth beneath the machined surface increased, the microhardness value got closer to the base material's microhardness. When turning Ti6Al4V ELI with PVD TiAlN insert, the microhardness difference was less than 2% at the initial machining time, which is 400 microns below the machined surface.

The material's surface and subsurface layers become more microhardness as the feed rate rises. After 300 to 500 microns below the machined surface, the thermal softening impact exceeds the work-hardening effect. Due to significant plastic deformation of the Ti6Al4V ELI's subsurface, a greater shearing force was produced during the turning process when PVD TiAlN was used instead of PVD AlTiN insert in a dry environment.

The microhardness of several points beneath the machined surfaces was lower than the bulk material of Ti6Al4V ELI because of the softening effect of the material at these levels, which was caused by the high cutting temperature created at the machined surface. The average microhardness of Ti6Al4V ELI is 340HV<sub>0.05</sub>. As the depth below the machined surface advances, the temperature impact decreases due to the low thermal conductivity of Ti6Al4V ELI, which is around one-sixth of steel material.

#### 4. CONCLUSIONS

Based on the dry turning of Ti6Al4V ELI using PVD coated AlTiN and TiAlN inserts, the following conclusions are drawn:

- As cutting speed increases microstructure heavily disturbed.
- Increasing cutting speed significantly alters the microstructure of the machined surface, likely due to increased heat generation and plastic deformation.
- A maximum microhardness of 398 HV0.05 was achieved at a cutting speed of 125 m/min and a feed rate of 0.20 mm/rev using PVD TiAlN inserts.
- Machining with PVD AlTiN inserts resulted in a general decrease in microhardness in both the surface and subsurface regions compared to TiAlN.
- The machining affected zone (MAZ) extended to 200  $\mu\text{m}$  and 300  $\mu\text{m}$  below the machined surface for PVD AlTiN and PVD TiAlN inserts, respectively, indicating a greater depth of influence with the TiAlN coating.
- While increasing cutting speed led to increased cutting temperature and thermal softening, the dominant effect in most cases was work hardening, leading to increased surface hardness.
- As cutting speed increases cutting temperature and thermal softening increases due to this flow stress, dislocation density decreases so surface hardness decreases.
- As feed decreases exposure of thermo-mechanical load increases so hardness of surface layer increases
- As the cutting speed increases, the flank wear is also increases.

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## Persian Abstract

چکیده

این مطالعه تأثیر پارامترهای برش را بر ریزسختی Ti6Al4V ELI در حین تراشکاری خشک با استفاده از درج‌های PVD AlTiN و TiAlN بررسی کرد. این تحقیق با پرداختن به چالش متعادل کردن بهره‌وری با الزامات یکپارچگی سطح سختگیرانه، تأثیر سرعت برش (۸۰، ۱۲۵، و ۱۷۰ متر در دقیقه) و نرخ تغذیه (۰.۰۸، ۰.۱۵، و ۰.۲۰ میلی‌متر بر دور) را بر ریزسختی زیرسطحی بررسی کرد. تست ریزسختی ویکرز تمایل به سخت شدن کار واضح را نشان داد، با بالاترین ریزسختی مشاهده شده در ناحیه زیرسطحی. افزایش سرعت برش با افزایش ریزسختی مرتبط است، به ویژه هنگام استفاده از درج‌های PVD TiAlN، که نشان دهنده درجه بیشتری از تغییرات ریزساختاری است. یک لایه سفید ضخیم‌تر پس از چرخش با درج‌های PVD AlTiN در مقایسه با PVD TiAlN مشاهده شد که احتمالاً به دلیل تفاوت در ضریب اصطکاک است. حداکثر ریزسختی (۳۹۸ HV0.05) با سرعت برش ۱۲۵ متر بر دقیقه و نرخ تغذیه ۰.۲۰ میلی‌متر بر دور با PVD TiAlN ثبت شد. منطقه تحت تأثیر ماشینکاری (MAZ) به ترتیب تا ۲۰۰ میکرومتر و ۳۰۰ میکرومتر زیر سطح برای درج‌های AlTiN و TiAlN گسترش یافت. این یافته‌ها بینش‌هایی را برای بهینه‌سازی فرآیندهای ماشین‌کاری برای افزایش یکپارچگی سطح و بهره‌وری در تولید اجزای Ti6Al4V ELI ارائه می‌کند.