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SURFACE INTEGRITY OF Ti-6Al-4V ELI WHEN MACHINED USING COATED CARBIDE TOOLS UNDER DRY CUTTING CONDITION

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ABSTRACT

Aerospace components from titanium alloys require the greatest reliability and satisfied surface integrity requirement. However, during machining of titanium alloys, the machined surface is easy damage because of the difficult-to-machine material and poor machinability. The aims are to investigate the surface integrity of Ti-6%Al-4%V ELI when machining under dry cutting condition. The results showed that the surface roughness values recorded were more affected by feed rate and nose radius geometry. Surface roughness was high value at the first machining followed by decreasing. Work hardening beneath the machined surface caused higher hardness than based material, on the other hand, over-aging caused the softening on machined surface of titanium alloy. Changing orientation of microstructure and 2 µm of white layer on the machined surface was found when turning at cutting speed of 95 m/min, feed rate of 0.35 mm/rev and depth of cut of 0.10 mm.

Keywords: Surface integrity, Ti-6Al-4V ELI, Surface roughness, Hardness, Dry machining.

INTRODUCTION

Study on surface integrity and surface finish of aerospace materials become a more critical issue, mainly, to produce a high quality of machined surface component, which requires high accuracy. The mechanical component, which designed from titanium alloys, has more difficult to produce a good-machined surface because of these alloys are difficult-to machine and high generated temperature when machining (Boothroyd and Knight, 1989; Che Harun, 2001). The surface integrity of titanium alloys is also affected by selected condition of machining. Requirement on the satisfied surface integrity is not only based on surface roughness but also focused on surface hardness, microstructure, plastic deformation of machined surface, residual stress and surface defects such as porosity, micro crack, stress concentration etc (Field and Kahles, 1971).

The surface finish determines the surface quality of machined component and the integrity obtained after machining. The surface integrity is defined as the inherent or enhances condition of a surface produced in machining (Field and Kahles, 1971).. Metal removal operations lead to the generation of surfaces that contain geometric deviation (deviation from ideal geometric) and metallurgical damage, which differs from the bulk material. The geometrical deviation refer to the various forms of deviations suck as roundness, straightness etc. Types of metallurgical surface damages that produced during machining include micro-crack, micro-pits, tearing, plastic deformation of feed marks, re-deposited materials etc. Its therefore, control of the machining process to produce components of acceptable integrity is essential. Machined components for aerospace application are subjected to rigorous surface analysis to detect surface damage that will be detrimental to the highly expensive machined components (Ezugwu *et al.,* 2003). The wide application of titanium alloys, included titanium alloy with 6 percent of aluminum, 4 percent of vanadium and extra low interstitial, for producing aero-engine components is due to their superior properties such as lightweight, superior mechanical at elevated temperature and excellent corrosion resistance.

Cutting tool materials employed for machining titanium alloys usually have short tool life and most react with titanium materials. This disadvantage is due to the generation of heat temperature closer to the cutting edge of tool (Trent, 1991). This phenomenon lead to rapid tool wears when machining titanium alloys. Hence, selection for suitable type of cutting tool and machined condition of machining titanium alloys is required to produce the good quality of machined surface. Cemented carbide tools selected, which are coated by TiN and TiCN layer(s) can reduce the wear on cutting tool, mainly on flank wear and crater wear (Ezugwu *et al.,* 2003). Che Haron (2005) found that the straight-cemented carbide tools were suitable used in turning Ti-6Al-4V. The hard coating layer(s) on the surface of cutting tools can reduce the tool wear progression on the flank face. The thin layer(s) from TiN and TiCN material reduced the friction between the cutting edge and work piece materials, so it will produce a smooth surface of titanium alloys and less surface damages. This paper investigates the integrity of machined surface by analyzing the surface roughness value recorded, surface damage and surface texture after machining Ti-6Al-4V ELI using coated cemented carbide tools and dry machining condition.

EXPERIMENTAL PROCEDURES

The workpiece material used in the machining trials was a titanium alloy alpha-beta Ti-6Al-4V Extra Low Interstitial (Ti-6Al-4V ELI), which is equiaxed α phase and surrounded by β in the grain boundary. At least 3 mm of material at the top surface of workpiece was removed in order to eliminate any surface defects and residual stress that can adversely affect the machining result (Kalpakjian and Rchmid, 2001). The machining trials under dry machining condition and high cutting speed were carried out using the Colchester T4 6000 CNC lathe machine. Tools and tool holders were selected based on the recommendation of the tool supplier (Kennametal, 2006). Chemical Vapor Deposition (CVD) inserts with designation KC9225 (CCMT 12 04 04 LF, ISO designation) were used to turn the titanium alloy Ti-6Al-4V ELI under dry cutting condition. Four layers of coating materials for each insert, which consist of TiN-Al2O3-TiCN-TiN, were selected. The parameters for turning operation are as shown in Table 1.

Table 1: Factors and levels used in the experiment

Factors	Levels		
	0	1	2
A- Cutting speed (m/min)	55	75	95
B- Feed rate (mm/rev)	0.15	0.25	0.35
C- Depth of cut (mm)	0.10	0.15	0.20

The average flank wear (*VB*) was measured by using a Mitutoyo Tool Maker Microscope at 20x magnification, and the machining time was recorded using a stopwatch. The wear and the cutting time were recorded at regular interval of one pass turning operation. The turning process was then stopped when *VB* reached 0.2 mm. The wear mechanisms of inserts were observed under the optical microscope. The detailed investigation of the worn out tool was carried out using Scanning Electron Microscope (SEM).

EXPERIMENTAL RESULTS AND ANALYSIS

Surface Roughness

Figures 1a, 1b and 1c show variation of recorded surface roughness values verse cutting time when machining Ti-6Al-4V ELI with coated cemented carbide inserts under dry cutting machining at various cutting speed of 55, 75 and 95 m/min, respectively. The curves show that extreme difference of surface roughness values when machining with different levels of feed rate (0.15, 0.25 and 0.35 mm/rev). Classically, The surface roughness values related to equation $h \approx f^2/8R$ or $h_{CLA} \approx f^2/18\ (3R)^{½}$ (Bhacharyya, 1998). Where, h is the peak-to-valley height, h_{CLA} the centerline–average roughness, f the feed rate and R the nose radius of insert. The formula shows that surface roughness is primarily dependent on the feed rate and the nose radius. These equations give ideal surface roughness values, which can only occurred when satisfactory cutting conditions are achieved. It is evident from the Figure 1 that the surface roughness is dependent on the feed rate whereby the use of lower feed rate produced better surface finish.

Figure 1a shows surface roughness values at the cutting speed of 55 m/min and at various feed rate of 0.15, 0.25 and 0.35 mm/rev. The surface roughness obtained for the feed rare of 0.25 and 0.35 mm/rev were higher at initial machining and then decreases non-regularly until the VB reached 0.2 mm. The surface roughness trends to become smoother toward the end of tool life. This is probably due to deformation of the flank wear or adherence of the workpiece material at the tool nose (Che Harun, 2001). Whereas according to Bhattacharya (1998), decreases of the surface roughness values recorded were caused by changed nose radius (become bigger). If the worn at nose radius to become wider, means that of produced the bigger the nose radius and smoother the surface roughness. For the feed rate of 0.25 mm/rev, there was a drop of surface roughness at the cutting time of 26.13 minutes. It was due to a chipping at nose radius, which has a length of 0.05 mm from the cutting edge.

Contrary to the surface roughness at the feed rate 0.15 mm/rev, the surface roughness values slightly increase as long as turning process. The highest surface roughness value obtained was 1.20 μm. It found when machining Ti-6Al-4V ELI at the end of tool life. The surface roughness value at the end of machining was higher than at the initial machining, it is probably due to chipping at nose radius and worn at the clearance face was more than at the flank face.

Figure 1b shows the surface roughness values recorded when machining Ti-6Al-4V ELI with coated carbide tools at the cutting speed of 75 m/min. Generally, the trend line of each curve is almost similar which has three forms. They are; the surface roughness value is high at first machining after then regularly decreases. At the second stage, the surface roughness is remained stable and followed by decreasing at final stage of tool life. This form is similar to three stage of the tool wear trend-line. The wear increases sharply at initial stage followed by regularly increased and then also dramatically increases at final stage. It can be seen at the Figure 1a, for the feedrate of 0.35 mm/rev, the surface roughness is 4.31 μm at the initial stage and decrease to 2.92 μm while the cutting time is 1.27 minutes. From the cutting time 1.27 minutes until 20.15 minutes, the surface roughness is remaining constant at around 2.92 to 2.97.

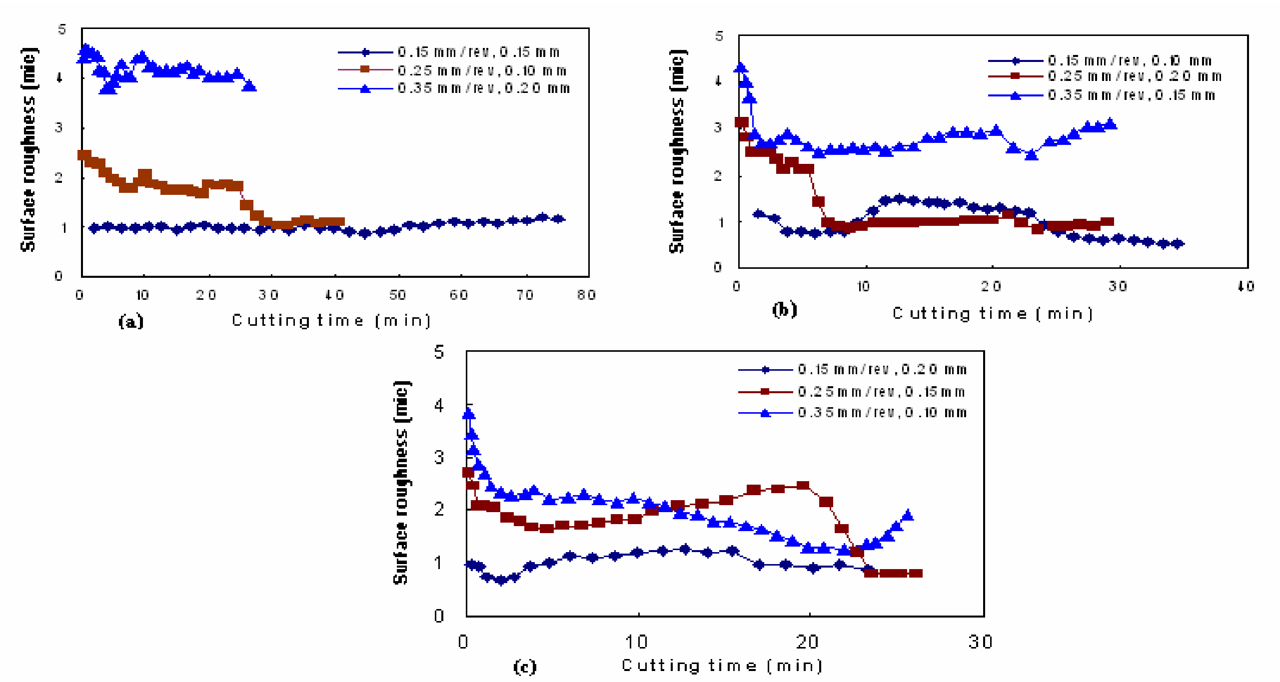

Figure 1: Surface Roughness Values Recorded at Cutting Speed of (a) 55 m/min, (b) 75 m/min and (c) 95 m/min

The similar trend line also found at the Figure 1c. Generally, it has three forms of the surface roughness as long as the machining process of Ti-6Al-4V ELI. Changed surface roughness as long as the turning process is most affected by the changing of geometry of tool nose radius.

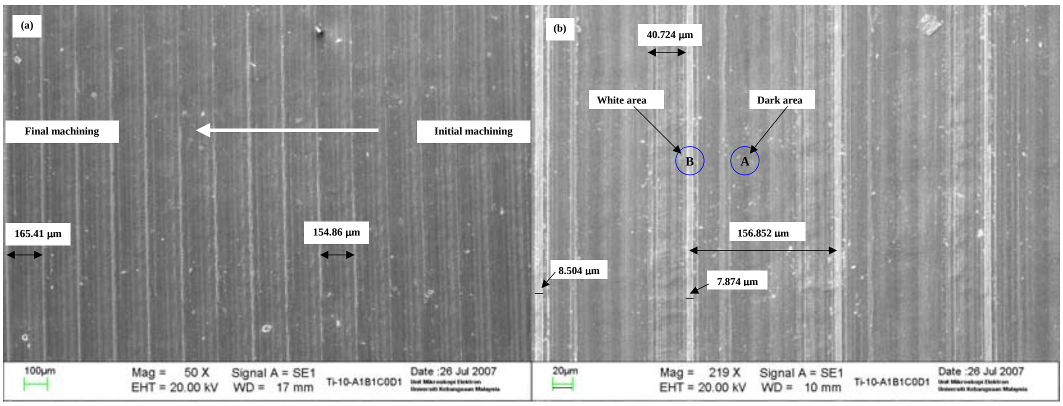

Figure 2: Surface Generated when Machining with Coated Cemented Carbide Insert Under Dry Machining (a) 50x Magnification and (b) 219x Magnification.

Figure 2 shows typical machined surface generated when machining Ti-6Al-4V ELI alloy with coated cemented carbide tools under dry machining. The machined surface generated consists of well-defined uniform feed marks running perpendicular to the tool feed direction. The major surface damages on the machined surface generated observed after machining Ti-6Al-4V ELI alloy with coated cemented carbide inserts are deformation of feed marks and re-deposited workpiece material (chip) onto already machined surface. This result is similar to the Ezugwu's previous research that found some damages on machined surface generated when machining Ti-6Al-4V alloy with PCD tools (Ezugwu, 2007). Three types of surface damages on machined surface of titanium alloy are deformation of feed marks, micro-pits and re-deposited of workpiece material. In Figure 2 is not seen a micro-pit. It is possibly due to the cutting speed when machining Ti-6Al-4V ELI with coated cemented carbide tool is still low (75 mm/min), whereas Ezugwu turned the workpiece Ti-6Al-4V with PCD tools at the cutting speed 200 m/min. With increasing the cutting speed will generate more heat that can produce more deformation and micro-pits.

Deformation of feed marks occurs as results of plastic flow of material during the cutting process. Plastic flow of material on the machined surface results in higher surface roughness values and higher residual stress levels (Zhou et al., 2003). Whereas re-deposited material of titanium alloy on the machined surface occurred when machining with conventional machining or dry machining. The deposited material originated from fine chip particles produced during the cutting process (Nabhani, 2001).

As shown in Figure 2(a) that a distance from the feed mark to next feed mark represents the feed rate when machining titanium alloy at cutting speed of 75 mm/min, feed rate of 0.15 mm/rev. and the flank wear reached 0.20 mm (cutting time of 34. 47 minutes). At the initial machining, the distance between two feed marks is 154.86 µm and its then increased to 165.41 µm at the final machining (increase in 10.55 µm). It was caused by the tool became a dull. When the cutting tool became a dull, it means that the nose radius became bigger, and changing in nose radius has a corresponding to the feed marks on the machined surface. During machining, the cutting tool replicates its nose on the machined surface (Sreejith and Ngoi, 2000). Similar results also found wide feed marks on the machined surface. It can be seen from Figure 2(b) that the wide feed mark is 7.874 µm and the next feed mark (end machining) is 8.504 µm or it increased of 8.46%. The wide feed mark occurs as a result of plastic flow that caused by changing in nose radius contacts to workpiece material. At the area of feed mark, it is possible, residual stress increased as effect of changing in microstructures.

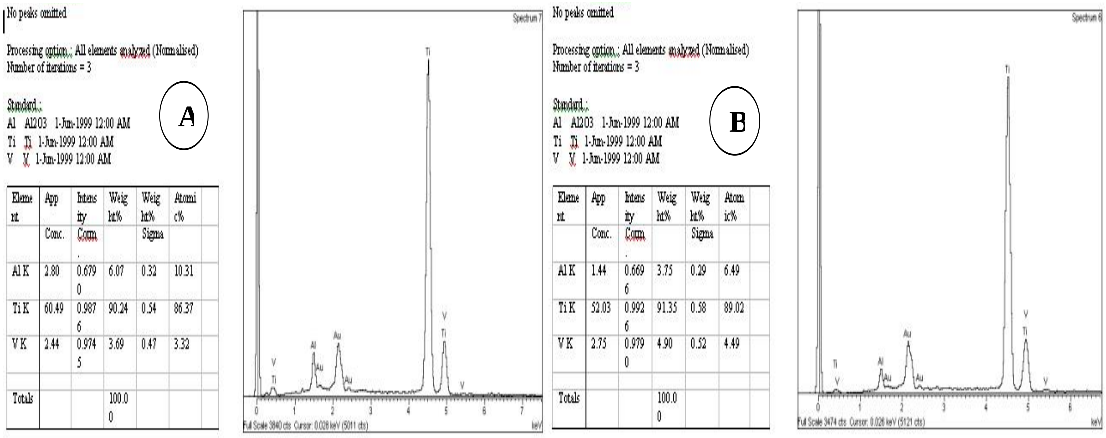

Figure 3: Chemical Composition of Machined Surface at Non-Deformed Surface (A) and Deformed Surface (B)

The differences of chemical composition of the machined surface between plastic flow area (B) and non-deformed area (A) are as shown in Figure 3. The chemical composition of Al decreased from 6.07 %wt to 3.75 %wt or decreased of 38.28 %. Whereas the composition of Ti and V increased from 90.24 %wt to 91.35 %wt (increased of 1.23 %) and from 3.69 %wt to 4.90 % wt (increased of 32.79 %), respectively. Changing in microstructures at the plastic flow due to high heat generated when machining process or over aging.

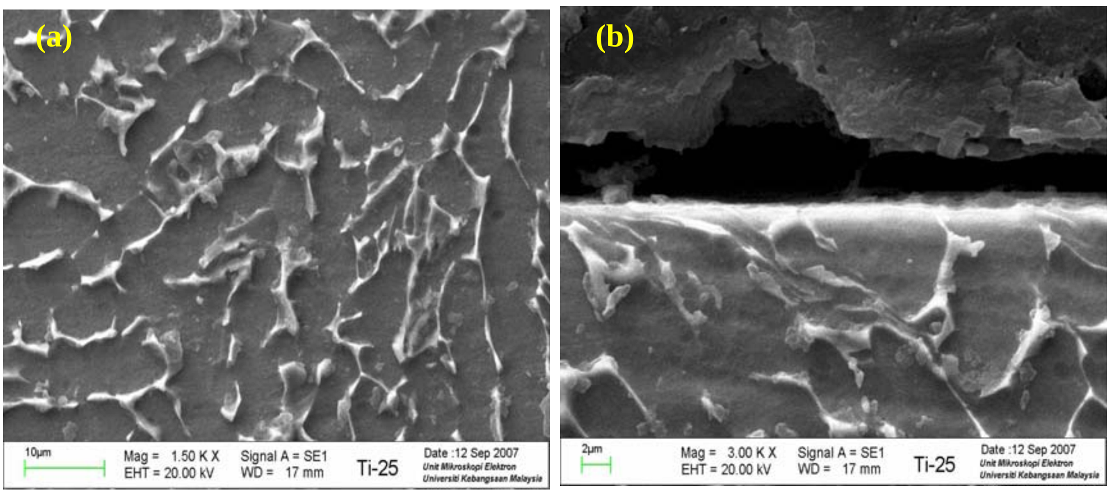

Figure 4: Microstructure below Machined Surface (a) and White Layer on Top Machined Surface (b) after machining with Coated Cemented Insert at a Cutting Speed of 95 m/min, a Feed Rate of 0.35 mm/rev and a Depth of Cut 0.10 mm

Sub-Surface Damages

Figures 4a and 4b are cross sections of machined surface after etching perpendicular to the tool feed direction. There was no evidence of sub-surface defects such as cracks, laps and visible tears after machining Ti-6Al-4V ELI alloy with the coated cemented carbide tools under dye machining. There was plastic deformation on the top layer of machined surface when machining Ti-6Al-4V ELI alloy at aggressive conditions involving cutting speed of 95 m/min, feed rate of 0.35 mm/rev and depth of cut of 0.10 mm. This suggest that severe shear stress generated under aggressive machining conditions coupled with high tool wear land have pronounce influence on the sub-surface deformation process.Che Haron (2001) has also reported that plastic deformation found on top layer of machined surface when machining Ti-6Al-4Vwith carbide tools at aggressive conditions of cutting speed of 100 m/min, feed rate 0.25 – 0.35 mm/rev and depth of cut of 2 mm. The cutting conditions employed in this study are typical of finish turning.

It can be deduced that the shearing force generated during the finishing operation can cause severe plastic deformation of sub-surface of Ti-6Al-4V ELI alloy due to a cutting action of the surface structure by the tool. A thin layer of disturbed or plastically deformed layer was formed immediately underneath the machined surface under dry cutting condition as shown in Figure 4b. The white layer or plastically deformed layer on the machined surface was found when cutting operation at cutting speed of 95 m/min, feed rate of 0.35 mm/rev and depth of cut of 0.10 mm and at the end of tool life. The thick of white layer formed was about 1.8 µm. Similar result found also by Che Haron (2001) when machining Ti-6Al-4V with straight tungsten carbide tools (CNMG 120408-883-MR4 tools) under dry cutting conditions and at cutting speed of 100 m/min, feed rate of 0.25 mm/rev and depth of cut of 2 mm. It is probably, prolonged machining with near worn tool produced severe plastic deformation and a thicker disturbed layer on the machined surface.

Surface Texture

The machined surface topography of coated carbide tool in three-dimensional figure was taken by confocal laser microscope. Figure 5 shows that the surface topography profiles at the end tool life and different parameter of the feed rate. Some peaks and deeper grooves were shown at machined surface as effect of feedrate factor. The distance between two peaks presents the feedrate selected.

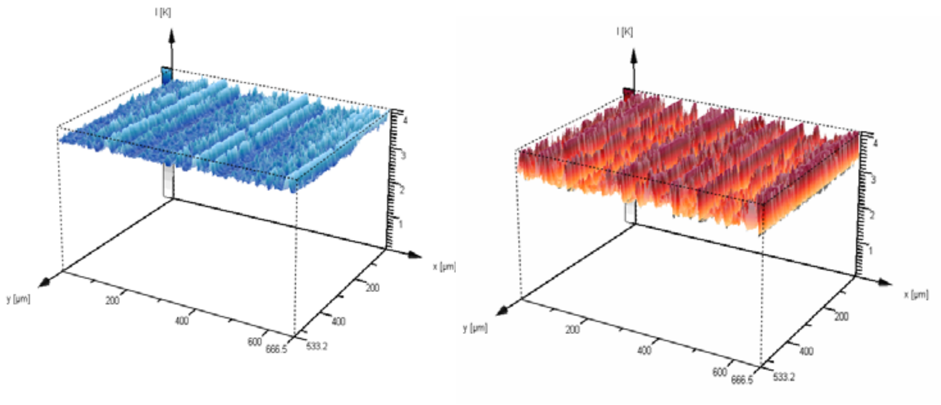

Figure 5. Surface Topography of Machined Surface after Machining of Titanium Alloys Ti-6Al-4V ELI by Using Coated Cemented Carbide Tools; (a) at cutting speed of 55 m/min and feed rate of 0.25 mm/rev (b) at cutting speed of 95 m/min and feed rate of 0.35 mm/rev

At the peaks, the surface roughness values are higher than depth groove. In Figure 5a, the machining of titanium alloy operated at feed rate of 0.25 mm/rev that results the surface roughness value is lower than Figure 5b, which operated at feed rate of 0.35 mm/rev. It is due to the effect the feed rate parameter. As mentioned before that the feedrate has a most significant effect on the surface roughness values compare to other parameters.

The surface roughness values present the surface topography condition of newest machine surface of workpiece material. The surface roughness value for Figure 5a and Figure 5b are 1.09 µm and 2.37 µm, respectively. The lower surface roughness produces the smoother surface topography. It can conclude that the surface topography has a strength correlation to the surface roughness.

CONCLUSIONS

The following conclusions are based on the results of turning Ti-6Al-4V ELI alloy with coated cemented carbide tools under dry machining.

1. Surface roughness values recorded when machining Ti-6Al-4V ELI alloy under dry condition investigated were more affected by feed rate and also by nose radius. Three stages of trend-line of surface roughness were high value at first machining followed by decreasing, remain stable at second stage and regularly decrease at final stage.

2. Surface finish generated when machining Ti-6Al-4V ELI alloy with coated cemented carbide tools are generally acceptable and free of physical damage such as cracks and tears. Effects of machining on turned surface were micro-pits, deformation of feed marks and re-deposited of titanium.

3. A 1.8 μm in thickness of white layer or plastically deformed layer on the machined surface was found when cutting operation at cutting speed of 95 m/min, feed rate of 0.35 mm/rev and depth of cut of 0.10 mm and at the end of tool life

4. The lower surface roughness value produces the smoother surface topography and it has a strength correlation to the surface roughness.

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