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The Influence of Cutting Heat on the Surface Integrity during Machining of Titanium Alloy Ti6Al4V

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Abstract
Machining of titanium alloys generates enormous amount of heat at the chip-tool interface leading to poor machinability. The current research investigates the effect of dry machining of Ti6Al4V on surface integrity of machined workpiece. A change in subsurface deformation was assessed by varying cutting speed and feed rate keeping the cut depth constant. Various output responses viz. cutting temperature, surface finish, induced strain, deformed depth, microhardness, etc. were discussed to evaluate the surface integrity. An optical microscopy, SEM and EBSD analysis performed on the machined edge showed deformation induced damage with microstructural restructuring which was correlated with chip microstructure. At lower cutting parameters, work hardening phenomenon however; at high cutting parameters thermal softening phenomenon becomes more dominant. This was derived with increased surface roughness, reduction in microhardness values beneath the machined surface and coarse microstructure obtained at higher cutting parameters. A Chip microstructural analysis validates the thermal softening and work hardening phenomenon where at high cutting speeds and feed rate the shear band formation is increased accompanied with increased chip segmentation frequency. However, at lower cutting parameters the reduction segmentation frequency and more deformed grains near shear band were observed.
Keywords: Surface integrity, temperature, thermal softening, work hardening, roughness, chip microstructure

1 Introduction

Surface integrity of machined component can be very critical aspect for maintaining the reliability of sensitive aeronautical components. However, this surface integrity can be damaged by machining process (Ginting and Nouari, 2009 and Edkins et al., 2014). Titanium alloys are attractive materials for

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aerospace applications because of their high strength to weight ratio and excellent corrosion resistance (Ginting and Nouari, 2009), (Edkins et al., 2014), and (Velásquez et al., 2010). Despite of these features the use of titanium alloys is still limited because of their poor machinability which is due to the properties like low thermal conductivity, high chemical reactivity, low elastic modulus, etc. (Velásquez et al., 2010). Low thermal conductivity of titanium alloys results into an increased cutting temperature at the cutting edge leading to premature tool failure and surface damage (Che-Haron, 2001). High chemical reactivity of titanium alloys results into strong welding of workpiece material at the tool tip affecting the machining process and increasing the production cost (Velásquez et al., 2010 and Che-Haron, 2001). Additionally, the low modulus of elasticity of titanium alloys further impairs its machinability by chatter marks on the workpiece during machining (Che-Haron, 2001). Machining is a costly process and accounts for 60% of the total cost of critical titanium aerospace components. To minimize costs, it is necessary to develop high metal removal techniques during machining of titanium alloys (Crawforth et al., 2012). However, use of higher cutting speed in for higher metal removal rate can further increase temperature and impair the machinability (Che-Haron and Jawaid, 2005, Tidu et al., 2015, Ravi Shankar et al., 2006, Patil et al., 2014, and Patil et al., 2015). Several studies have been carried out for analyzing the effect of various cutting parameters on surface integrity of the machined titanium alloy Ti6Al4V. Previous researches reported the variations in the surface integrity in terms subsurface grain deformations, subsurface microstructure alteration, white layer formation, residual stresses, etc. The depth and the micro-structure of this deformed layer depend not only on the machining parameters but also on the mechanical and physical properties of the material. The subsurface microstructural alteration was reported with the formation of twins (Tidu et al., 2015, Ravi Shankar et al., 2006). Many researchers have carried out the analysis of effect of material composition and process parameters on chip formation mechanism and chip microstructure during machining of titanium alloys (Joshi et al., 2014). However, a lesser amount of research was discovered which is focusing on correlation between surface integrity, subsurface deformations and chip microstructure during machining of titanium alloy Ti6Al4V. Furthermore, an optimized process parameters in controlling the grain deformations are also needs to be investigated. Thus the current research investigates the effect of various cutting parameters on surface integrity and subsurface deformations. During the analysis, various output parameters such as cutting temperature, surface roughness, subsurface grain deformations, microhardness of deformed grains, etc. were measured. An optical microscopy and SEM with EBSD was performed to reveal the subsurface deformations and microstructural alterations, etc. The phenomenon of work hardening and thermal softening affecting the surface integrity was further analyzed and correlated with chip microstructure.

2 Experimental set-up and machining conditions

Face turning operation was performed on titanium Ti6Al4V using MAZAK Turn Mill center as shown in Figure 1. The certified mechanical properties and chemical composition of titanium AMS 4928 from TIMET are presented in Table 1.

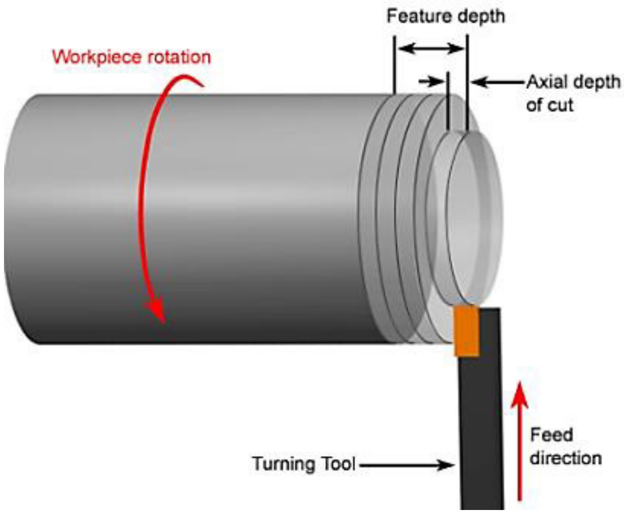


Figure 1: Face turning setup

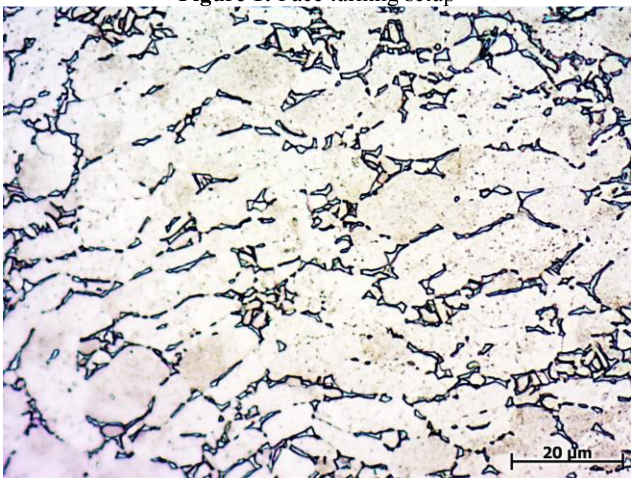


Figure 2: Microstructure of As Received Ti6Al4V

Figure 2 shows the microstructure of as received specimen in longitudinal direction showing equiaxed grains of α-phase with β-phase.

Table 1: Mechanical properties and chemical composition of Ti-6Al- 4V

Mechanical Properties		Chemical Composition
UTS (MPa)	988	Fe (%) 0.15
YS (Mpa)	899.7	Al (%) 6.52
Hardness (HRC)	32	V (%) 4.07
		Ti (%) Remainder

Table 2 shows the cutting parameters and cutting conditions used during the face turning experimentation. Total 4 sets of experiments were performed for the analysis.

Table 2: Cutting Parameters and Cutting Conditions

Experiment No.	Cutting Parameters
Experiment No.1	V_c 40 m/min, f 0.2 mm/rev, a_p 1.0 mm
Experiment No.2	V_c 90 m/min, f 0.2 mm/rev, a_p 1.0 mm
Experiment No.3	V_c 140 m/min, f 0.2 mm/rev, a_p 1.0 mm
Experiment No.4	V_c 140 m/min, f 0.5mm/rev, a_p 1.0 mm
Cutting Tool	CNMG 120408MS KCU 10
Cutting Condition	Dry

First 3 sets of experiments with one replica of each experiment were carried out to analyze the effect of increase in cutting speed on surface integrity. However, Experiment No.4 was performed with an increase in feed rate from 0.2 mm/rev to 0.5 mm /rev at highest cutting speed of 140 m/min, to analyze the combined effect of increased cutting speed and feed rate on surface integrity and subsurface deformations during machining of titanium alloy Ti6Al4V. The surface finish of the machined sample was measured using Mahr Pocket Surf. The cutting temperature during machining was measured using thermal imaging camera FLIR P 640. During this, Ti-6Al-4V material was heated at 300 °C in a furnace. The temperature was measured with thermocouple and thermal camera at the same time. Emissivity of material in the thermal camera was set such that, the temperature readings from thermocouple and the camera are identical. The emissivity of Ti-6Al-4V thus obtained was 0.34 at 300 °C. The chips and the machined surfaces were collected after each trial with proper identification.

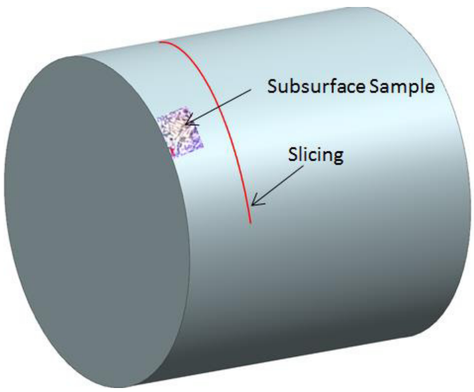


Figure 3: Sample cutting for subsurface analysis

As shown in Figure 3, the surface undergone face turning operation was sliced along the periphery and was cut into equal slices such that the surface beneath machined edge is used as sample for metallurgical observations. Each of the selected samples was subjected to sample preparation and etching procedure for optical microscopy, scanning electron microscopy and EBSD.

3 Results and Discussions

3.1 Cutting Temperature

The cutting temperature generated during machining of titanium alloys plays important role in the subsequent surface integrity of the machined workpiece. The excessive heating can lead to reduction in tool life (Che-Haron and Jawaid, 2005). The cutting temperature was measured using thermal imaging camera FLIR P 640. Figure 4A-4D shows the images captured for maximum cutting temperature recorded using thermal imaging camera for during Experiment No. 1 to Experiment No.4

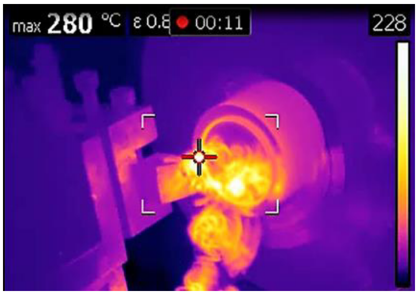


Figure 4A: Maximum cutting temperature Experiment 1

Figure 4B: Maximum cutting temperature-Experiment 2

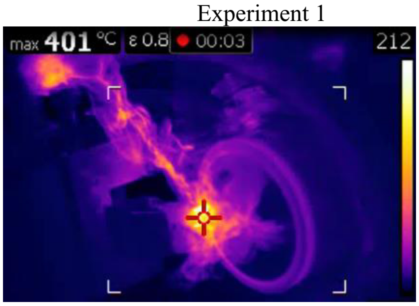


Figure 4C: Maximum cutting temperature Experiment 3

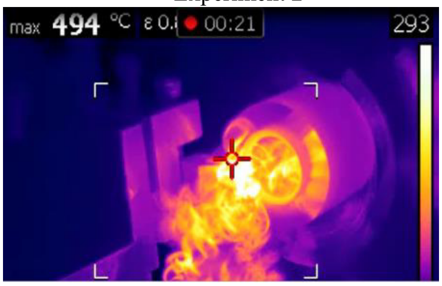


Figure 4D: Maximum cutting temperature-Experiment 4

It was found that with an increase in the cutting speed; the contact between chip and tool increases which ultimately increased the amount heat generated at the cutting zone (Joshi et al., 2014). Additionally, low thermal conductivity of titanium further contributed to an increased cutting temperature during machining. It was also found that an increase in the feed rate at higher cutting speed leads to an increased amount of friction between tool and workpiece which further increased the cutting temperature (Joshi et al., 2014).

3.2 Surface Finish

Surface finish of the machined workpiece is one of the most critical parameter during machining of titanium alloy Ti6Al4V as there will be a direct effect of any change in cutting temperature, cutting forces on the subsequent surface topography (Joshi et al., 2014). The surface finish was measured along the cutting direction interns of average surface roughness R_a over the periphery where 10 readings were taken for each experiment and an average reading was used for comparative analysis. As shown in Figure 5, the surface roughness increases with an increase in the cutting speed from Experiment 1 to Experiment 3. This increase in cutting speed leads to an increase in cutting temperature and further the tendency of titanium alloy to adhere to the tool face which ultimately leads to formation of BUE (Built-Up-Edge). All these factors affect the surface topography and hence increase the surface roughness (Che-Haron and Jawaid, 2005). An increase in feed rate from 0.2 mm/rev to 0.5 mm/rev in Experiment 4 resulted into increased amount of friction leading to higher cutting temperature which contributed to BUE formation resulting to poor surface finish (Patil et al., 2015 and Joshi et al., 2014).

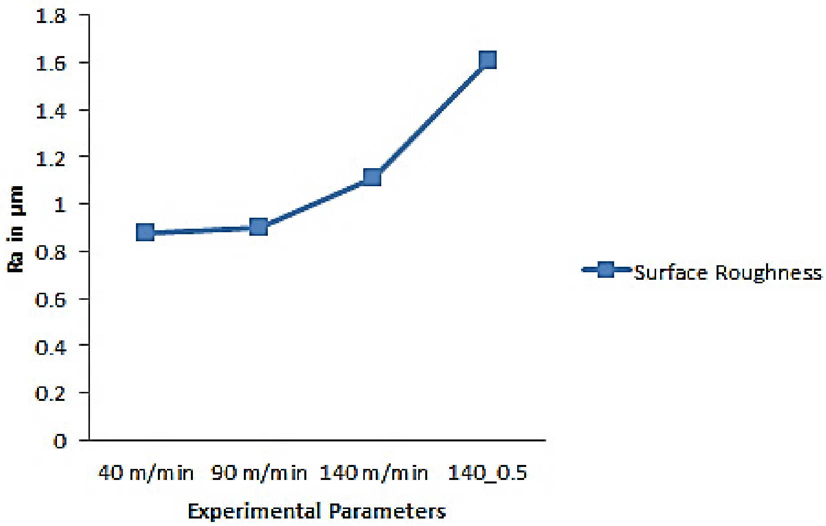


Figure 5: Effect of cutting parameters on surface roughness

3.3 Subsurface alterations

Previous researchers identified three distinct regions near the machined surface (Edkins et al., 2014). Figure 6 represents 3 deformed regions D1, D2 and D3.

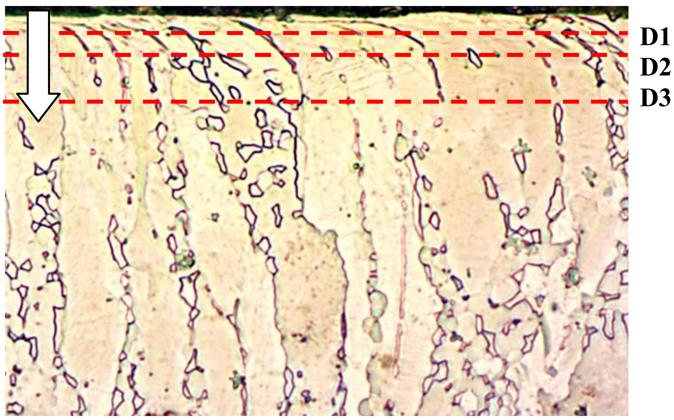


Figure 6: Subsurface Deformation regions

The region D1 is just beneath the machined surface and it composed of highly deformed grains. The region D2 is beyond region D1 and is composed of grains with moderate deformations. The region D3 is composed of machining unaffected grains. As shown in Figure 7, the effect of various cutting parameters on the deformation of grains was measured by measuring the deformation depth and strain in the corresponding grains. The deformation depth and shear strain values were measured using Image analyzing software and optical microscopy. With an increase in the cutting speed and feed rate the deformation depth as well as the shear strain in the deformed grain increases.

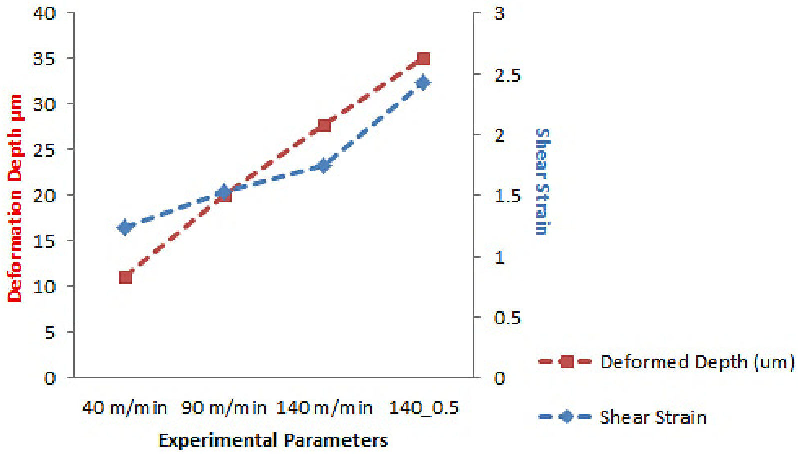


Figure 7: Effect of cutting parameters on surface roughness

The cutting temperature plays an important role in the subsurface deformation phenomenon. An increase in the cutting speed and feed leads to increased cutting temperature and subsequent thermal softening which resulted to an enlarged deformation depth beneath the machined surface (Edkins et al., 2014). Figure 8A-D shows the SEM micrographs of the deformed grains beneath the machined surface.

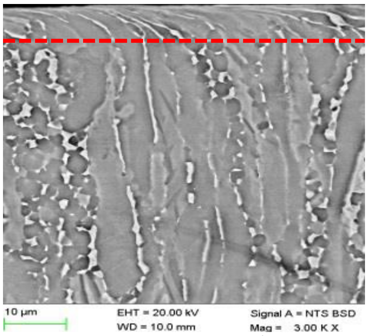


Figure 8A: Experiment 1

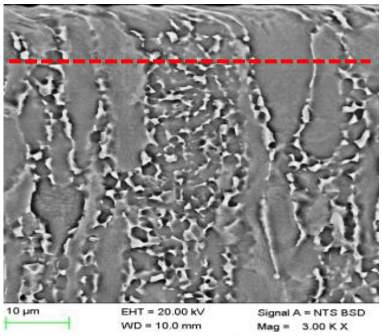


Figure 8B: Experiment 2

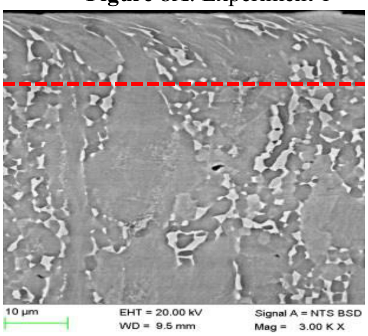


Figure 8C: Experiment 3

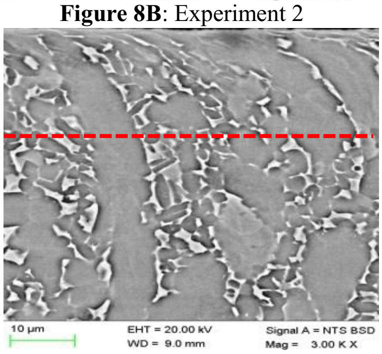


Figure 8D: Experiment 4

Figure 8A-D: SEM Micrographs of Grain Deformations

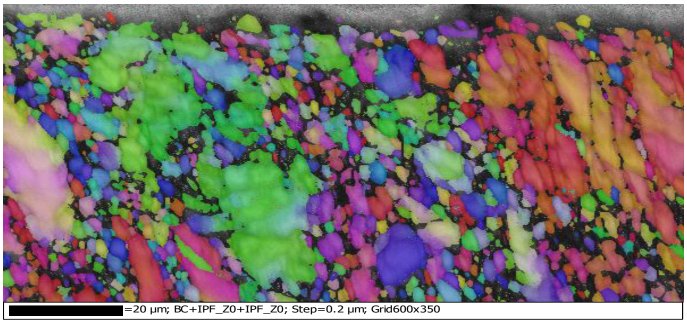


Figure 9: EBSD of Machined surface at Experiment 4

As shown in Figure 9, EBSD reveals the damage with the grains at the subsurface level at extreme cutting parameters of Experiment 4. The said damage was with the single grain or similar oriented structure unit (Crawforth et al., 2012). Thus, from the recorded images it can be seen that the severity of plastic deformation beneath the machined surface can be controlled by varying the cutting parameters (Ginting and Nouari, 2009). An increased amount of cutting speed and feed rate will lead to amplified subsurface deformations during machining of titanium alloy Ti6Al4V. Work hardening phenomenon resulting from deformed grains near subsurface area resulted in higher microhardness than that of base material. The microhardness of the deformed region was measured along the depth of the deformed zone for each Experiment. As shown in Figure 10, with an increase in the level of cutting parameter, the amount heat generated at the cutting zone increases contributing to more amount of thermal softening. This thermal softening effect becomes dominating over the work hardening phenomenon which otherwise becomes more dominant at the lower level of cutting conditions (Che-Haron, 2001). However, the effect of increase in cutting speed on thermal softening and microhardness was found to be uniform only to a depth of 0.2 mm beneath the machined surface. A combined effect of low thermal conductivity and an over aging of titanium alloys can be responsible for the thermal softening at the deformed zone (Ginting and Nouari, 2009). Figure 11A-B shows the microstructure details at the machined surface for Experiment 1 which was at lowest level of cutting condition and Experiment 4 which was at highest level of cutting condition. The micrographs reveals that an increased cutting temperature and the overaging effect resulted into a coarse equiaxed microstructure during Experiment 4 which further caused a reduction in microhardness at the surface when compared to the fine microstructure obtained during Experiment 1.

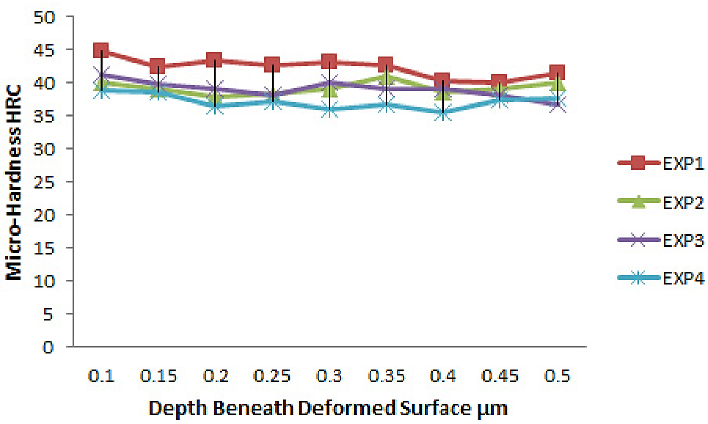
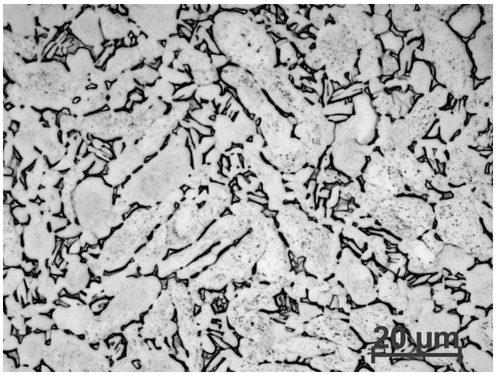


Figure 10: Microhardness at the deformed surface



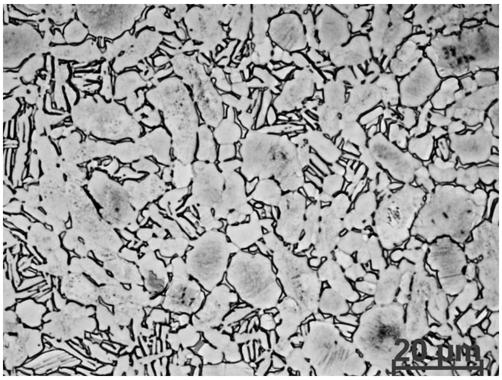


Figure 11A: Microstructure at Experiment 1 **Figure 11B:** Microstructure at Experiment 4

3.4 Chip Microstructure

Chip microstructure reveals various important aspects of actual machining conditions (Joshi et al., 2014). Chip microstructure consists of shear bands, crack formation, grain deformations, etc. Shear bands in the chip microstructure represent localized deformation of material in narrow zones. The surrounding area of shear band remains unaffected. This localization of shear band leads to drastic changes in cutting forces which can affect the cutting tool performance (Patil et al., 2015 and Joshi et al., 2014). As shown in Figure 12A-D, an increase in the level of cutting parameters from Experiment 1 to Experiment 4, leads to higher cutting temperature at the cutting zone, which further causes more amount of thermal softening and shear band formation. At Experiment 1 with less cutting speed of 40 m/ min, work hardening phenomenon appeared to be more dominant over the thermal softening as the segmentation frequency appears to be reduced and the grains around the shear band appears to be more elongated. Chips at Experiment 4 which was at a cutting speed of 140m/min and a feed rate of 0.5 mm/rev showed branching of shear bands which was nothing but the significance of higher cutting temperature, thermal softening and increased chip segmentation frequency (Patil et al., 2015 and Joshi et al., 2014). The spacing between the shear bands is an important parameter which determines the segmentation frequency and amount of thermal softening (Patil et al., 2015). The spacing between shear bands was measured on the optical micrographs of chips and the frequency of segmentation was calculated using formula (Joshi et al., 2014).

$$f_{chip} = V/w \tag{1}$$

Where f_{chip} = frequency of segmentation in Hz, V = cutting speed in m/min, w = shear band spacing.

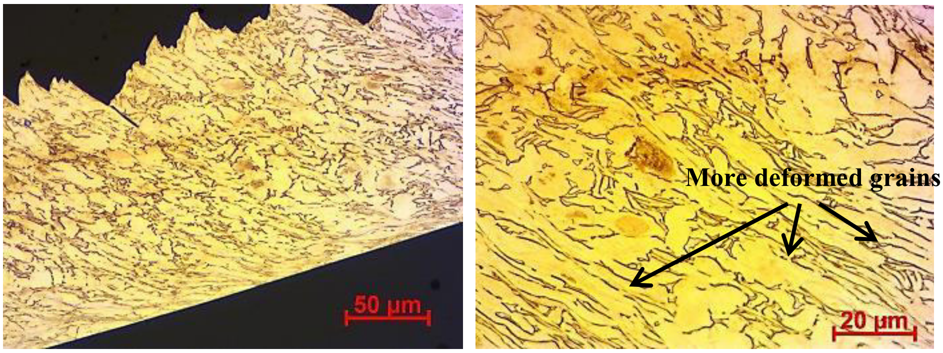


Figure12A: Shear band formations at Experiment 1

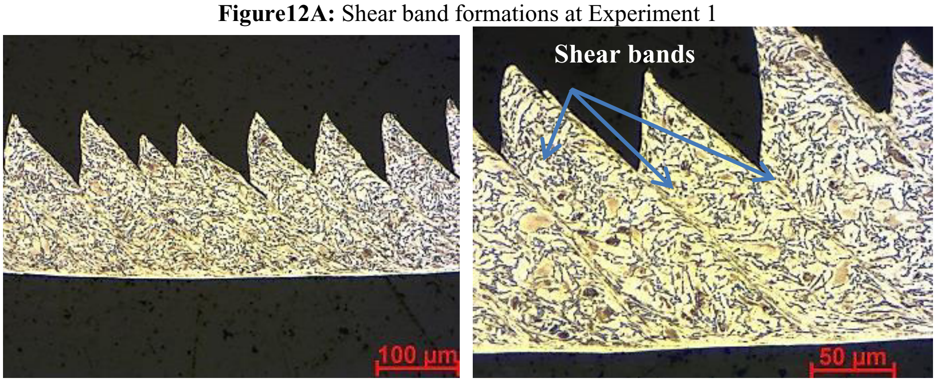


Figure12B: Shear band formations at Experiment 2

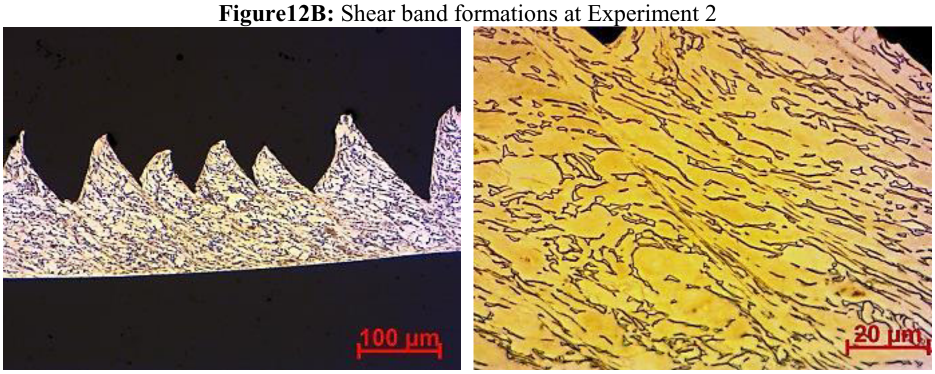


Figure12C: Shear band formations at Experiment 3

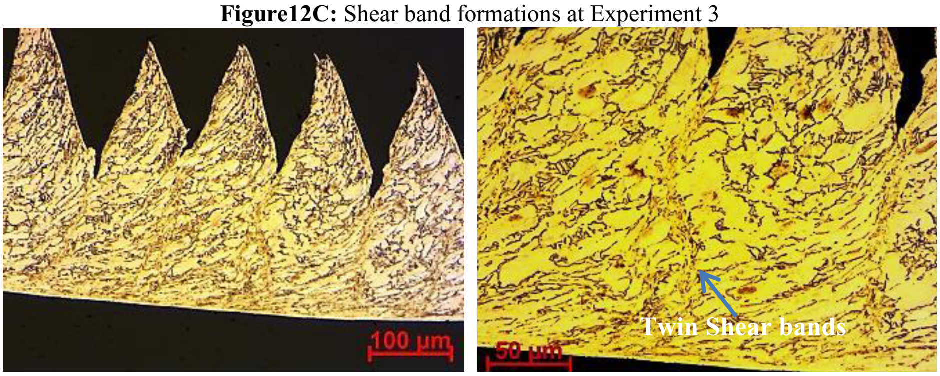


Figure12D: Shear band formations at Experiment 4

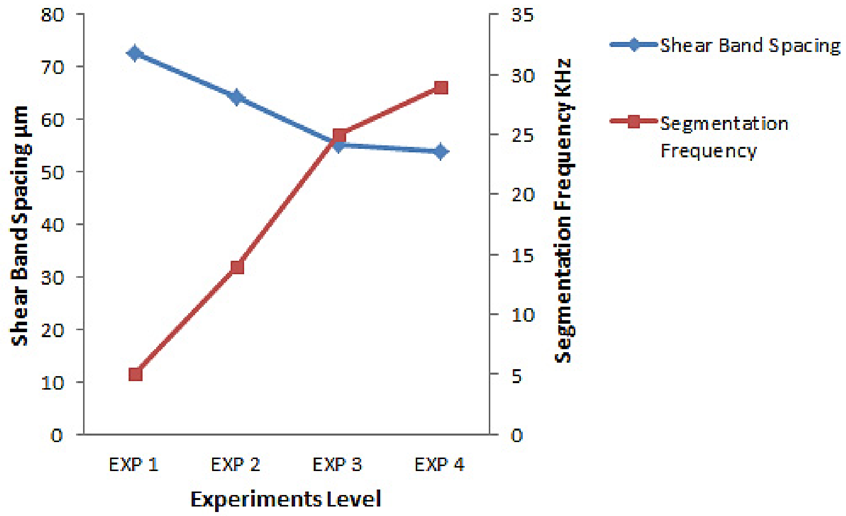


Figure 13: Shear band spacing and Segmentation frequency

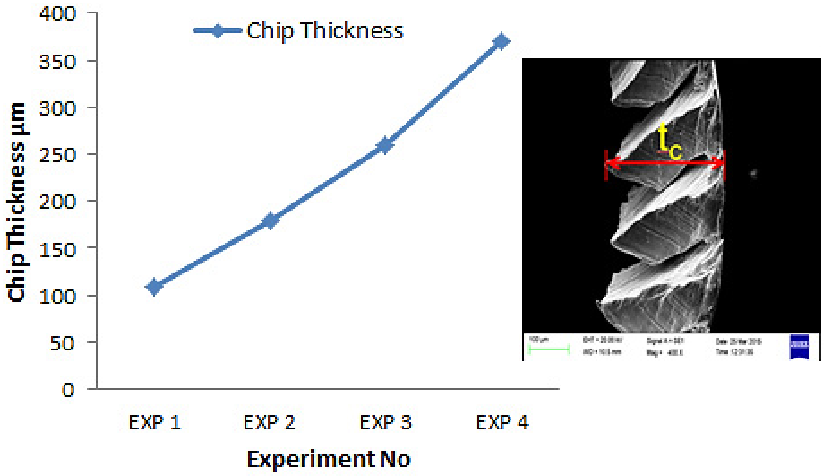


Figure 14: Chip Thickness

As shown in Figure 13 and Figure 14, with an increase in the cutting speed the increase in tool workpiece contact ratio and with an increase in the feed rate the increase in the friction between the tool and workpiece collectively leads to an increased amount of chip thickness, cutting heat, thermal softening, shear band formation and increased chip segmentation frequency (Joshi et al., 2014).

4 Conclusions

The surface integrity of machined workpiece of titanium alloy Ti6Al4V is highly dependent on the cutting parameters and the subsequent work hardening and thermal softening behavior of the work material. Following specific conclusions can be drawn from the present work:

- An increase in the cutting speed from 40 m/min to 140 m/min and an increase in the feed rate from 0.2 mm/rev to 0.5 mm/rev lead to higher cutting temperature at the cutting zone because of enhanced contact between tool and workpiece and hence increased friction.
- At lower cutting parameters, work hardening phenomenon however; at high cutting parameters thermal softening phenomenon was found to be more dominant. This was derived from increased surface roughness and reduction in microhardness values beneath the machined surface along with coarse microstructure obtained at higher cutting parameters.
- With the increase in level of cutting parameters from Experiment 1 to Experiment 4, depth of deformed grains beneath the machined surface and the corresponding strain in those deformed grain was found to be increased.
- Chip microstructure analysis supported the thermal softening and work hardening phenomenon where at high cutting speeds and feed rate, the chip thickness and the subsequent shear band formation was increased accompanied with reduction in shear band spacing. At lower cutting parameters, less segmentation frequency was observed with increased grain deformations along the shear band.
- From experimental analysis it was found that to obtain uniform surface integrity, subsurface deformations and chip microstructure, a cutting speed below 90m/min and feed rate of 0.3 mm/rev at a constant depth of cut of 1 mm can be recommended.

References

Che-Haron C.H. Tool life and surface integrity in turning titanium alloy. Journal of Material Processing Technology 2001; 118: 231-237.

Crawforth Pete, Wynne Bradley, Turner Sam, Jackson Martin. Subsurface deformation during precision turning of a near-alpha titanium alloy.Scripta Material 2012; 67: 842-845.

Che-Haron C.H. and Jawaid A. The effect of machining on surface integrity of titanium alloy Ti–6% Al–4% V. Journal of Materials Processing Technology 2005; 166: 188-192.

Edkins Kyle D, Rensburg Nickey Janse van, Laubscher Rudolph F. Evaluating the subsurface microstructure of machined Ti-6Al-4V. Procedia CIRP 2014 ; 13: 270-275.

Ginting A and Nouari M. Surface integrity of dry machined titanium alloys. International Journal of Machine Tools & Manufacture 2009; 49:325-332.

Joshi Shashikant, Pawar Pravin, Tewari Asim, Joshi Suhas S. Influence of β phase fraction on deformation of grains in and around shear bands in machining of titanium alloys. Materials Science & Engineering A 2014; 618: 71-85.

Joshi Shashikant, Pawar Pravin, Tewari Asim, Joshi Suhas S. Effect of b phase fraction in titanium alloys on chip segmentation in their orthogonal machining. CIRP Journal of Manufacturing Science and Technology 2014; 7: 191-201.

Patil Sandip, Joshi Shashikant, Tewari Asim, Joshi Suhas S. Modelling and simulation of effect of ultrasonic vibrations on machining of Ti6Al4V. Ultrasonics 2014; 54: 694-705.

Patil Sandip, Pawar Pravin, Jadhav Shital, Supare Ashish, Powar Amit, Kekade Swapnil, Dr. Singh. Correlation between heat treatment, microstructure and machinability for Ti6Al4V. International Journal of Mechanical And Production Engineering 2015; 3: 6.

Ravi Shankar M, Rao Balkrishna C, Lee Seongeyl, Srinivasan Chandrasekar, King Alexander H, Compton Dale W. Severe plastic deformation (SPD) of titanium at near-ambient temperature. Acta Materilia 2006; 54: 3691-3700.

Tidu A, De Saever A, Schuman C, Bolle B, Chevrier P. Machining of Pure High Grade Titanium: Effect on the Subsurface Microstructure. International Journal of Metallurgical & Materials Engineering 2015; 1: 108.

Velásquez Puerta J.D., Tidu A, Bolle B, Chevrier P, Fundenberger J. Sub-surface and surface analysis of high speed machined Ti–6Al–4V alloy. Materials Science and Engineering A 2010; 527: 2572–2578.