

## ANALYSIS OF CHIP PRODUCED IN FREE MACHINING OF Ti-6Al-7Zr-3Nb-4Mo-0.9Nd AND Ti-5Al-7Zr-7Nb-0.7Nd ALLOYS

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### ABSTRACT

*The use of Titanium and its alloys in modern era can never be discarded. Continuous developments in many industries like aviation and power generation increased its use in many applications, not only because of its chemical properties but also because of its excellent properties including, high strength to density ratio, withstand with high stresses, better fatigue and corrosion properties and ability to resist high temperatures. However, all these properties of this alloy results in poor machinability, hence, make the automatic machining of these alloys nearly difficult. The main limitation of titanium and its alloys is that it produces long chips during machining which tangled around tool, hence; reduce tool life and sometime leads to fracture during conventional turning (CT). In recent days new two alloys are developed named Ti-6Al-7Zr-3Nb-4Mo-0.9Nd and Ti-5Al-7Zr-7Nb-0.7Nd with better performance in machining. These two developed alloys contain 0.9% and 0.7% neodymium by weight, respectively. It produces discontinuous chips during metal cutting, which make possible the automatic machining. It also reduces machining time and increase productivity. Ultrasonically assisted turning (UAT) was used to further improve its machinability. In addition, machinability of both newly developed alloy and Ti-6246 is studied by analyzing chip compression ratio, chip thickness and shearing angle. Overall, chip compression ratio is greater for UAT as compared to CT, which shows improved machinability.*

**KEYWORDS:** Free-machining; alloy; Machinability; Chip formation process; Ultrasonically assisted turning; Titanium alloy.

### INTRODUCTION

Titanium and its alloys are introduced in the early 1950s to get high-strength to weight ratio in aerospace industries. These alloys became very popular and counted as backbone materials for many applications, such as chemical industries, aerospace and energy sides [Muhammad et al, 2013A, Muhammad et al, 2013B]. There are many titanium alloys present which are used for different purposes and having different composition. Each alloy has their specific mechanical properties [Youssef, 2008]. Over all, titanium alloys have high toughness and tensile strength [Donachie, 2004]. These alloys keep their strength even at very high temperatures. In addition, these alloys have light weight, surprising resistance to corrosion and capability to endure maximum temperature [Muhammad et al, 2014A, Muhammad et al 2014B]. The high cost bound use of titanium alloys to military applications, medical devices, aircrafts, spacecraft, sports equipment and components of luxury sports cars which one designed to bear high stress, such as connecting rods of luxurious sports cars and some first-class sports equipment. The final product of titanium alloy is too

costly because of the high titanium alloy, fabrication and machining cost [Arrazola et al, 2009]. Machining cost is high for titanium alloy because of its very high strength.

However, it is necessary to machine titanium alloys (Turning, drilling, facing, reaming, boring, taper turning etc.) to convert raw material into final product which could use for many purposes. The main disadvantage related to titanium alloys, that in conventional machining it has poor machinability [Muhammad et al, 2012A, Muhammad et al, 2012B, Muhammad et al, 2012C, Muhammad et al, 2012D, Muhammad et al, 2012E, Machai and Beirmann, 2011]. High strength, chemical reactivity and low thermal conductivity at maximum temperature of titanium alloys lead to short life of cutting tool [Arrazola et al, 2009]. Because of low young's modulus of titanium alloys, it leads to chatter and spring-back which produce poor surface quality of the final product. In addition, titanium and its alloys produce long continuous chips during conventional machining (Turning and drilling) which tangled around the tool and make it difficult to machine titanium alloys using automatic machine setup [Donachie, 2004].

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In practice, the machining parameters are kept low to increase tool life and also produce fine surface finish. At the other hand, the low levels of feed rate and cutting speed increases the productivity time which alternatively increases the cost of product. For titanium alloys recommended values of cutting speed and feed rate is in the range of 0.2-0.63 m/s and 0.15-0.2 mm/rev, respectively [Arrazola et al, 2009].

Chip morphology, in titanium alloys machining play a key role which is affected by machining parameters [Sima and Ozel, 2010]. In general, it depends on some parameters such as cutting speed, tool geometry, depth of cut and feed rate. Chip morphology is categorized in continuous chips having same chip thickness across the cross section, segmented chips that has completely separated segments and having saw tooth like shape [Maurotto et al, 2014]. [Groover, 2010], stated that, high-speed cutting of titanium alloy leads to segmented chips, which have separated segments and discontinuous chip.

Similarly, various attempts were made to achieve discontinues chips by doping low melting rare earth metals in titanium alloys. In this regards, the addition of lanthanum particles in Ti-6246 and Ti15V3Al3Cr3Sn have resulted a discrete and discontinues chip formation [Maurotto et al, 2014].

In the current study, two newly developed alloys Ti6Al7Zr3Nb4Mo0.9Nd and Ti5Al7Zr7Nb0.7Nd were machined with ultrasonically assisted turning (UAT) and conventional turning (CT) processes and the produced chips were analyzed to investigate the effect of

Neodymium (Nd) in discontinues chip formation compared to the original Ti-6246 alloys.

### Experimental Setup

The developed alloys were provided by the technical Universities Bruanshweig and were machined at Loughborough University, Loughborough, UK using both UAT and CT processes. The resulted chips were used in the current study to investigate the effect of Nd on chip formation in both UAT and CT [Muhammad et al, 2016, Muhammad et al, 2017, Ullah et al, 2017, Muhammad, 2013].

The collected chips at various cutting conditions presented in table 1 were initially analyzed with a naked eye and visible difference in chips produced was observed in both UAT and CT for both modified alloys. The chips were then mounted in Bakelite powder for further analysis to investigate the chip compression ratio, chip thickness and shear angle formation. The machine used for mounting is manufactured by MARUMOTO, made by Japan and is available in Mechanical Engineering Department of University of Engineering & Technology (UET), Peshawar. The machine has temperature gauge, pressure gauge, time buzzer, pressure relief valve, press and plunger. There is also backlit powder and oil used in mounting press machine. For polishing, the facility available at Centralized Resource Laboratory (CRL) of Peshawar University, Physics department was used. After polishing the samples, they were loaded to the OLYMPUS, Model PMG3 light microscope and high resolution images at various resolutions were taken.

**Table 1: Cutting parameters used in experimental tests**

Cutting Technique	Cutting Speeds (m/min)	Depth of cut ( $\mu\text{m}$ )	Feed rate (mm/min)
CT	10	300	0.1
	20		
	30		
UAT	10		
	20		
	30		

Similarly, for good resolution images, a Scanning Electron Microscope (SEM) manufactured by JEOL (Model JSM-5910) was also used. Its magnification capability is up to 300,000 times, accelerating voltage ranging from 0.3 to 30 kV. Its resolution is 3.0 nm at 30kV. It provides Backscattered electron and secondary electron imaging. This SEM has stub for sample mounting, vacuum chamber where the stub is placed for analysis. SEM is connected to a Computer through data cables. Monitor display the magnified images. Controller is connected to computer, which control Scanning Electron Microscope magnification and positioning of magnification area of sample.

The chemical composition of chips sample were

carried out using energy-dispersive X-ray spectroscopy (EDX), which is manufactured by OXFORD instruments, Model is INCA-2000 and made by United Kingdom (UK) and is present in Centralized Resource Laboratory (CRL), Peshawar University. The images collected for the collected chips at various cutting conditions were then further analyzed for chip compression ratio, chip thickness and shear angle.

## RESULTS AND DISCUSSIONS

### Chip Morphology

During turning process of both modified alloys Ti-6Al-7Zr-3Nb-4Mo-0.9Nd and Ti-5Al-7Zr-7Nb-0.7Nd,

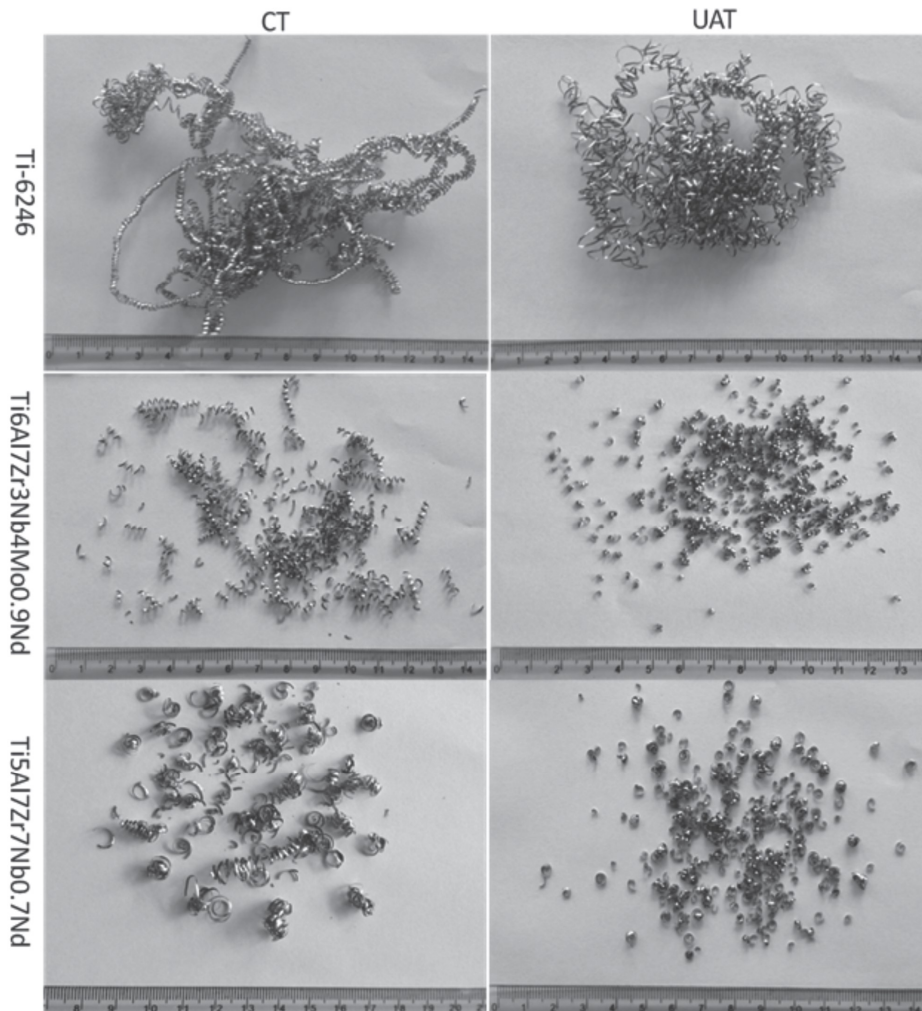


Figure 1: Collected chip in CT and UAT of the studied alloys

short discontinuous chips is produced both in UAT and CT while standard titanium alloy, Ti-6246 produced long continuous chips as shown in Figure 1. Ti-6Al-7Zr-3Nb-4Mo-0.9Nd and Ti-5Al-7Zr-7Nb-0.7Nd alloys have resulted discontinuous chips at all tested cutting conditions. During the machining process of Ti-6Al-7Zr-3Nb-4Mo-0.9Nd and Ti-5Al-7Zr-7Nb-0.7Nd alloys, the process zone temperature reaches approximately 400-800°C as a result the Nd particles melts and discontinuous chips are produced in both CT and UAT. The discontinuity in chips is further enhanced in UAT at all tested cutting conditions and can be attributed by the high process zone temperature presented by Muhammad et al [Muhammad et al, 2013A, Muhammad et al, 2013B, Muhammad et al, 2012E] low energy impact imposed by vibrations. During the process when tool penetrates in workpiece, temperature localizes in primary shear zone which results diminished adhesion between the segments and the segments separated with further tool

advancement. Where as in Ti-6246, there are no particles of Nd present therefore, produces long continuous chips.

### Chip Compression Ratio

Chip compression ( $\lambda$ ) ratio was analyzed for all three tested alloys for better understanding of the chip formation process. The images collected during light microscopy and scanning electron microscopy analysis were further used for chip compression ratio calculation. The chip compression ratio was calculated using equation 1.

$$\lambda = \frac{H_{\max} + H_{\min}}{2d_c}, \quad (1)$$

where  $H_{\max}$  is the maximum height of peaks in the produced chip,  $H_{\min}$  is the minimum height of peaks and  $d_c$  is overall chip thickness as shown in Figure 2.

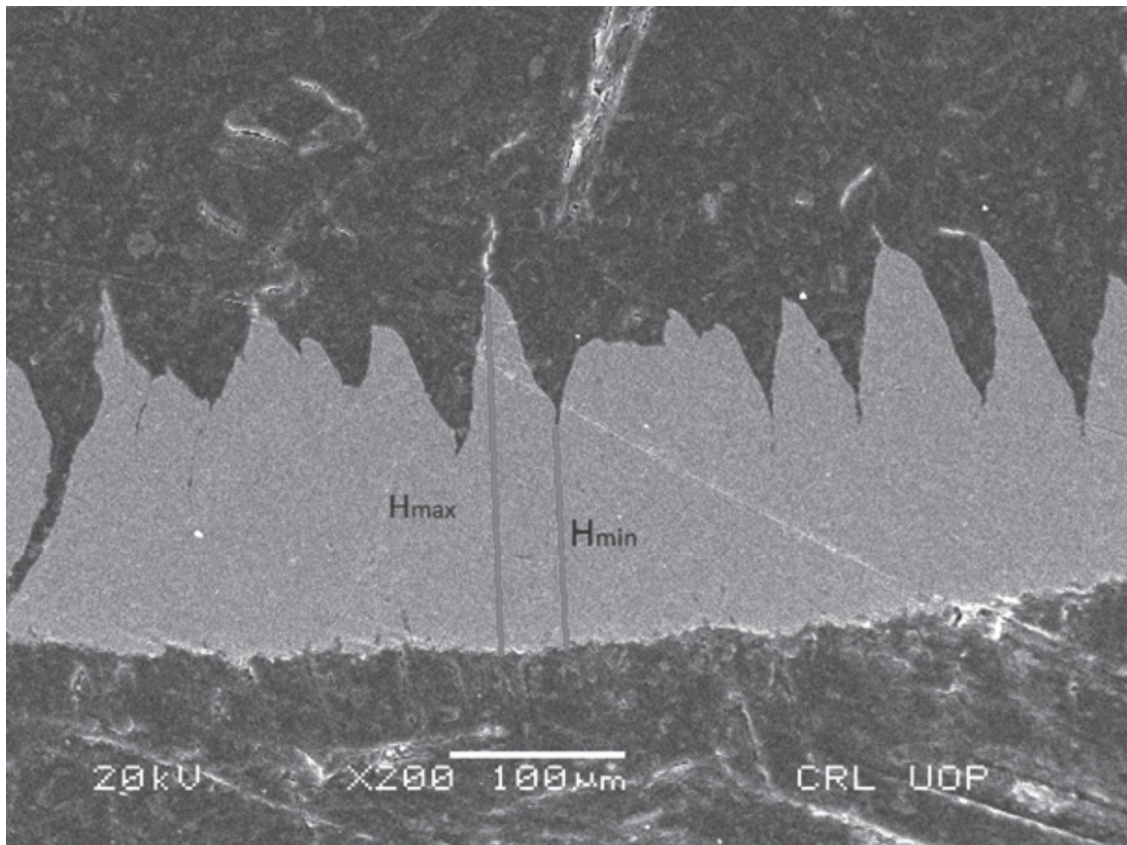


Figure 2: Minimum and maximum peaks height of chip



The calculated chip compression ratio in both UAT and CT for Ti-6246 is presented in Figure 3. A slight increase in chip compression ratio was observed with an increase in cutting speed as expected [Groover, 2010]. The variation in the level of chip compression ratio calculated in UAT and CT is minor at tested cutting conditions and as a result continues chips were produced.

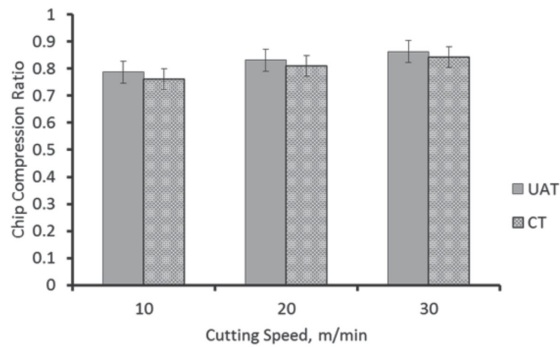


Figure 3: Chip compression ratio of Ti-6246 chips at various cutting speeds

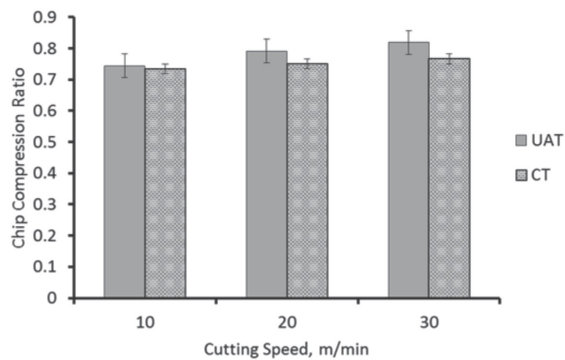


Figure 4: Chip compression ratio of Ti6Al7Zr3Nb4Mo0.9Nd chips at various cutting speeds

Similarly, a slight decrease in the chip compression ratio was observed for Ti6Al7Zr3Nb4Mo0.9Nd alloy in both UAT and CT (see Figure 4). The Nd particles at the grain boundaries become soft or melt and highly serrated and broken chips were produced in both UAT and CT.

The reduction in chip compression ratio in Both UAT and CT was significant in Ti5Al7Zr7Nb0.7Nd alloy as presented in Figure 5. Hence, resulted highly broken serrated chip formation at all tested cutting condition.

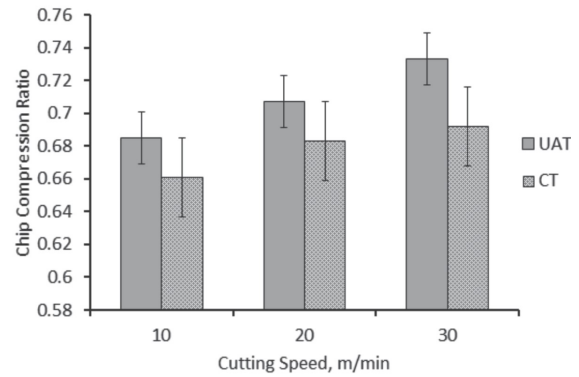


Figure 5: Chip compression ratio of Ti5Al7Zr7Nb0.7Nd chips at various cutting speeds

### Shear Angle

Angle of plan where shearing occurs between two consecutive layers of chips as shown in Figure 6, It is an important term to analyze chips. According to Groover [Groover, 2010] shear angle have inverse relation with chip thickness.

$$\phi = \tan^{-1} \left( \frac{r \cos \alpha}{1 - r \sin \alpha} \right) \quad (2)$$

$$r = \frac{t_f}{t_o} \quad (3)$$

Where  $\alpha$  is rake angle of the tool,  $r$  is chip thickness ratio,  $t_f$  is final thickness of the chip after machining and  $t_o$  is chip thickness before machining.

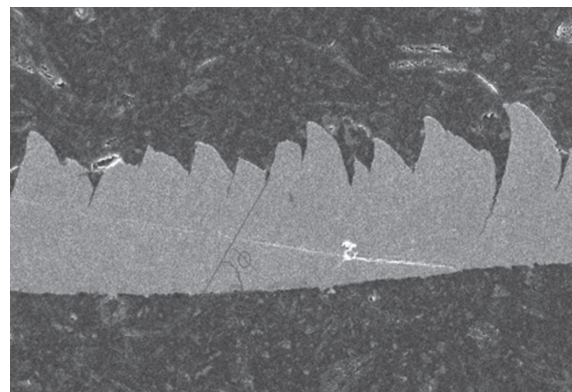
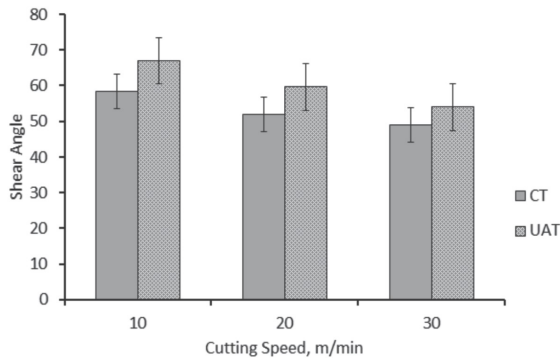
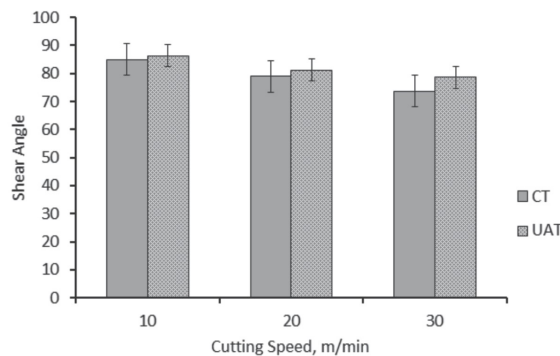


Figure 6: Shear angle in a chip

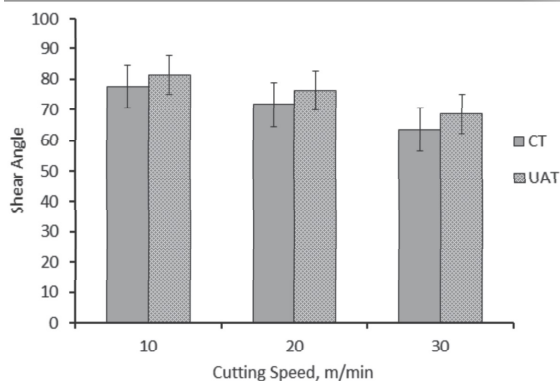
The calculated shear angle for Ti-6246 is presented in Figure 7. An average shear angle of 58°, 52° and 48° in CT was calculated at 10, 20 and 30 m/min cutting speed, respectively. The calculated shear angle in UAT in Ti-6246 alloys was approximately 6-10° higher than



**Figure 7: Calculated shear angle of chip produced from Ti-6246 alloy**



**Figure 8: Calculated shear angle of chip produced from Ti6Al7Zr3Nb4Mo0.9Nd alloy**



**Figure 9: Calculated shear angle of chip produced from Ti5Al7Zr7Nb0.7Nd alloy**

CT. The shear angle reduced with an increase in cutting speed in UAT as well.

A high magnitude of shear angle was calculated for Ti-6Al-7Zr-3Nb-4Mo-0.9Nd and Ti-5Al-7Zr-7Nb-0.7Nd in both UAT and CT at all tested cutting conditions as shown in Figure 8 and Figure 9, respectively. The

formation of high shear angle and the presence of Nd particle accelerate the formation of broken chips in both UAT and CT and discontinuous chips are produced. Comparing the two modified tested alloys, Ti-6Al-7Zr-3Nb-4Mo-0.9Nd alloy has the maximum calculated shear angle level in both UAT and CT.

## CONCLUSIONS

The newly developed alloys named Ti-6Al-7Zr-3Nb-4Mo-0.9Nd and Ti-5Al-7Zr-7Nb-0.7Nd responded very well in both UAT and CT at different cutting conditions when compared to old parent alloy Ti-6246 in terms of discontinuous chips produced. The addition of Nd particles as inter grain impurity enhanced the chip broken process in both UAT and CT. The 0.7% (wt) of Nd particle responded well to the formation of discontinuous chip formation.

In addition to that, when compared CT, vibro-impact phenomenon in UAT at the tool-workpiece-interface and the higher process zone temperature improved the breakability of chips resulted discontinuous and serrated chips formation.

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