

Microstructural Analysis of Ultrasonic Vibration Assisted Turning of Ti alloy Ti-6Al-4V

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INTRODUCTION

Ultrasonic assisted turning (UAT) is a novel manufacturing technology where high frequency vibrations are imposed on conventional movement of cutting tool [1-2, 5-6]. This technique is used to improve the machinability of 'difficult-to-cut' materials [2]. Various parameters in UAT such as vibration frequency, vibration amplitude and cutting speed can vary the cutting forces during the process [5]. Several researchers have studied the effect of these vibrations assisted techniques on machining of 'difficult-to-cut' materials such as Inconel 718, but very few have used this technique effectively for the machining of Ti alloy Ti-6Al-4V and to study the effect of vibrations on microstructural changes in Ti alloy during machining. Mitrofanov et al. [7] performed the microscopic analyses of surface layers of Ni-base superalloy Inconel 718, machined with ultrasonic vibrations. A transformed surface layer (about 25 μm thick) was observed after conventional turning, whereas there are no visible alterations in the surface layer structure for ultrasonic turning. Babitsky et al. [5] found that the UAT method performs better at low cutting speed using high frequency and high amplitude of vibration. Koshimizu [6] found that a reduction in cutting forces was observed during UAT of Ti-6Al-4V. The author also found that the vibration assisted technique holds good for Ti-6Al-4V, only when the cutting speed is 30% below the maximum vibrating velocity of the cutting tip. Nath and Rahman [3] studied the effect of machining parameters during UAT of Inconel 718.

Therefore, the objective of this work is to analyze the effects of UAT of Ti-6Al-4V, in terms of chip morphology, chip microstructure, surface quality assessment, cutting temperature and cutting forces, etc. by using experimentation technique.

EXPERIMENTAL TECHNIQUE

An elaborated experimental set up was developed for the UAT of Ti-6Al-4V. The set up preparation includes design and fabrication of vibrating tool assembly which consists of transducer, booster, horn or tool holder and a tool tip, etc. "Fig. 1" shows the experimental set up developed for UAT.

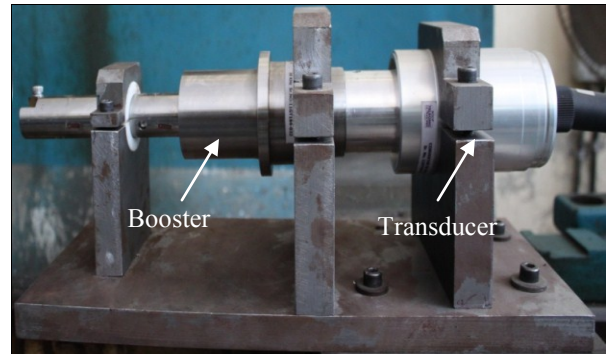


Fig.1: Experimental set up for UAT

The vibrations were given to the tool in the feed direction. A hollow pipe of titanium (Ti-6Al-4V) of 93 mm outer diameter and 1 mm thickness was used as a workpiece for OD turning for this experimentation. Dry machining was carried out for both UAT and CT. Table 1 shows various cutting conditions used for this experimentation. When the cutting tip is vibrated ultrasonically in the direction of feed, then the following limitation is imposed:

Feed direction:

$$\text{Feed velocity } (s*n) < \text{Vibrating tip velocity } (V_t)$$

Where, s – feed mm/rev and n – spindle RPM

In all the experiments, feed velocity used was much lower than vibrating cutting tip velocity of 2513 mm/s. Therefore, the condition of ultrasonic vibration assisted cutting is satisfied. An ultrasonic vibration in the feed direction improves the machining productivity and is known as sweep cutting [5].

Table 1: Cutting conditions

Workpiece	Ti-6Al-4V, Dia. 93mm
Cutting tool	KENNAMETAL (DNMG 150608)
Cutting Speed	20 m/min
Feed rate	0.1 mm/rev
Depth of cut	0.1 mm
Cutting	DRY

* corresponding author

A frequency of 20 kHz and an amplitude 20 μm was used for the experimentation on Ti-6Al-4V during UAT. The experimental results were analysed for process study as well as for microstructural study of chip formation process during conventional turning (CT) and ultrasonic assisted turning (UAT).

MICROSTRUCTURAL ANALYSIS AND DISCUSSION

A. NANOINDENTATION ANALYSIS

To study the influence of UAT and CT processes on the microstructure of surface layers of treated materials, nanoindentation tests were carried out (On model TI-900). “Fig. 2” shows nanoindentation results on surfaces machined using CT and UAT processes. It is seen that the hardened surface layer for UAT is lower than that of for CT. Average hardness value on UAT surface is 3.98 GPa, which is 16% less than the average hardness of CT surface layer i.e. 4.74 GPa. “Fig.2a-b” shows the microstructure of the cross-sectional surface of the specimen, where the nanoindentation tests were carried out for both UAT and CT machined surfaces.

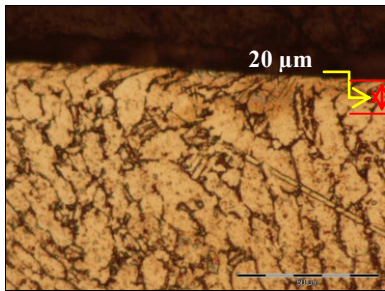


Fig.2a: UAT surface

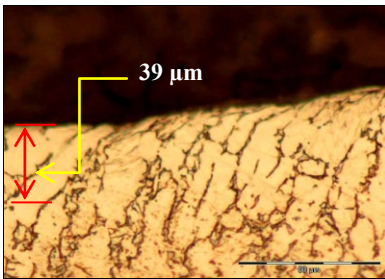


Fig.2b: CT surface

Fig.2a-b: Optical images of the specimen on the cross-sectional surfaces during UAT and CT

(V_c -20 m/min, s -0.1 mm/rev, f -20 kHz, a -20 μm)

It is observed that, the grains in CTed surface are highly deformed as compared to those in UAT. This can be correlated with the results obtained from nanoindentation tests. As the highly deformed grains make the surface much harder, the CT generates a relatively harder surface layer. On the other hand, less deformed grains are evident on UAT machined surface, which indicates lower machined surface hardness. The shear strain values of the deformed grains are measured using image analyser software. The depth for the deformed grains in UAT surface was 20 μm and that of in CT surface was 39 μm. The maximum strain measured on the deformed grains on UATed surface was 1.27, and that for CTed surface was 2.9. Therefore, a 50% reduction in the shear strain in the

deformed grains is observed during UAT over that of in CT.

B. CHIP SEGMENTATION

In this section, quantitative data on chip morphology during UAT and CT machining is presented. It includes chip thickness, segment pitch, crack angle, included angle, width of segment and shear band width, etc. as shown in Fig.3. This data were obtained from SEM and optical images of chips generated during machining using an image analyzer software.

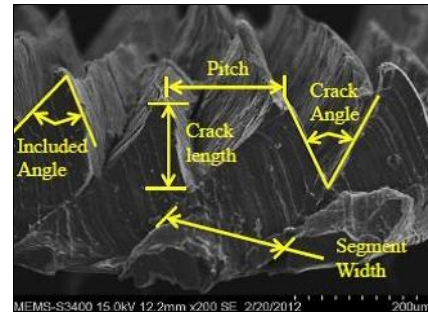


Fig.3: Terminology used to specify dimensions of chip segment

“Fig.4a-b” shows SEM images for the chips obtained during CT and UAT. The chip thickness measured for CTed chip was 132 μm and that for UATed chip was 95 μm. Therefore, an 18 % reduction in chip thickness is observed in UAT process over that in CT process.

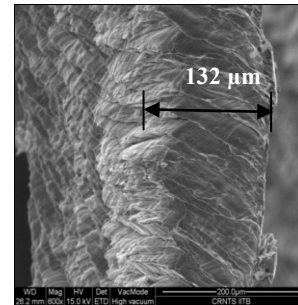


Fig.4a: CTed - chip

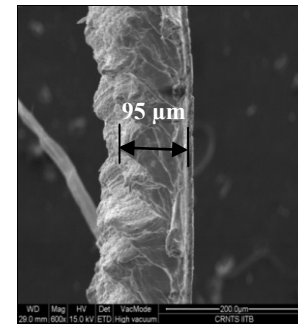


Fig.4b: UATed- chip

Fig.4a-b: SEM images for the CTed and UATed chips

It is observed that a reduction in cutting temperature during UAT leads to a reduction in thermal softening and hence increases the chip length per softening. During CT, with an increase in the cutting temperature with the cutting speed, the thermal softening increases, this reduces chip length per softening, see Fig.5.

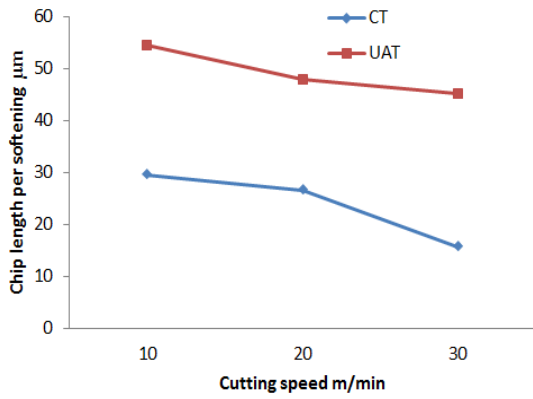


Fig.5: Effect of an increase in cutting speed on chip length per softening during UAT and CT

At a cutting speed of 30 m/min both CT and UAT experiences higher cutting temperature. Therefore, a decrease in chip length per softening was recorded at this cutting speed than that of at 10 and 20 m/min. A quantitative data on chip morphology during UAT and CT machining is tabulated as shown in Table 2. It is evident from the table that UAT reduces the severity of the machining process on Ti alloys as compared to CT.

Table 2: Chip segmentation

Chip segmentation	Improvement in UAT	Significance
Chip thickness	18% reduction	Lower chip compression factor
Segment pitch	48% increase	Higher normal stresses
Chip length per softening	45% increase	Less thermal softening
Segment Width	45% increase	More shear band spacing
Crack angle	23% decrease	Less brittle nature of material
Included angle	23% decrease	Less plastic deformation
Chip compression factor	18% reduction	Minimum plastic deformation
Shear angle	50% increase	Less cutting forces

C. CHIP MICROSTRUCTURE

Shear bands obtained in the chip microstructure represent localized deformation of material in small zones [8]. The surrounding area remains almost unaffected. Due to shear localization, the tool is subjected to drastic changes in cutting forces, which adversely affects the tool life and integrity of machined work surfaces. The microstructure of chips obtained with and without ultrasonic vibrations to the cutting tool at a cutting speed of 20 and a feed rate of 0.1 mm/rev is as shown in Fig.6a-b

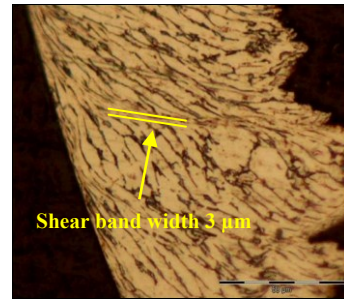


Fig.6a: CTed chip-20m/min

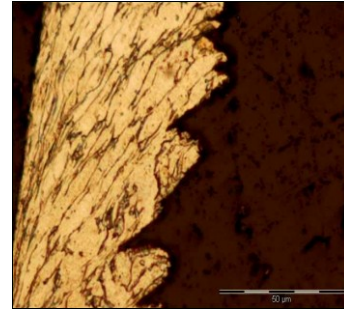


Fig.6b:UATed chip-20m/min

Fig.6a-b: Microstructure of CTed and UATed chips during CT and UAT at a cutting speed of 20 m/min.

It is observed that there is no shear band formation in the chips generated during UAT, whereas in CT, a shear band of width 3 µm was observed. During CT, since there is a continuous interaction between tool and chip, heat continues to generate which leads to localized thermal softening and thus formation of shear bands [8]. However, in case of UAT, since there is an intermittent cutting, it leads to less heat concentration and hence no shear band formation is observed. Normal stresses are responsible for crack formation on shear plane [8].

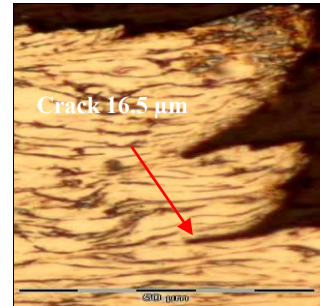


Fig.7a: CTed chip-20m/min

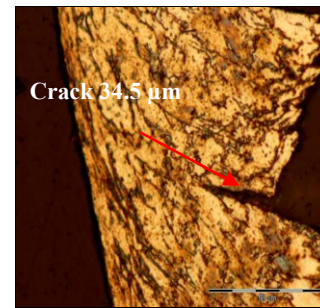


Fig.7b:UATed chip-20m/min

Fig.7a-b: Crack formation at the chips during CT and UAT

As shown in Fig. 7a-b, a crack length at the shear plane during CT was 16.5 μm and that during UAT was 34.5 μm . Therefore, during CT, a reduction in crack length in the chips shows smaller intensity of normal stresses on shear plane. However, during UAT large crack appears on the shear plane which shows high intensity of normal stresses. This is also responsible for tearing of material on the shear plane, which results in less reactive forces on a cutting tool.

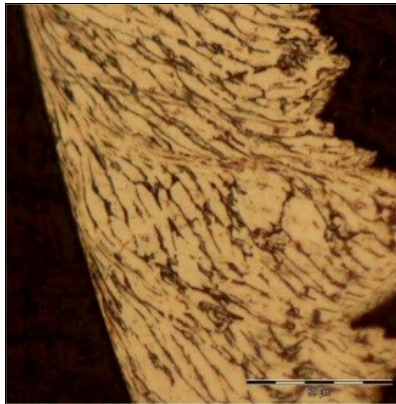


Fig.8a: CTed chip-20m/min

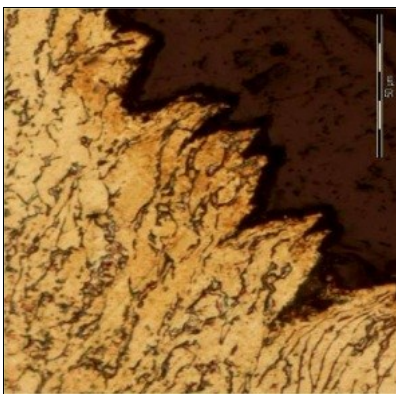


Fig.8b: UATed chip-20m/min

Fig.8a-b: Grain structure at the chips during CT and UAT

It is observed that grains in the CT chips are more elongated as than that of in UAT, see Fig. 8a-b. These elongated and small width grains make the chip harder which exerts significant abrading forces on the cutting tool. However, during the UAT, significant elongation in the grains does not appear. It shows recovery taking place during machining process [8]. Thus, chips appear completely strain relieved, which also means less hardened during UAT. These chips exert less reactive forces on the cutting tool.

D. MACHINED SURFACE QUALITY

Surface finish of machined workpiece is extremely sensitive to changes in machining process. Hence, it was used as a criterion to identify the special characteristics during both UAT and CT process. The roughness of machined surface was measured in terms of R_a (average surface roughness) during

both UAT and CT. ‘Veeco Surface Profilometer’ was used to measure the R_a value. As shown in Fig.9a, ultrasonic vibration assisted machined surfaces have a matte finish. However, the conventionally machined surfaces have a glossy finish.

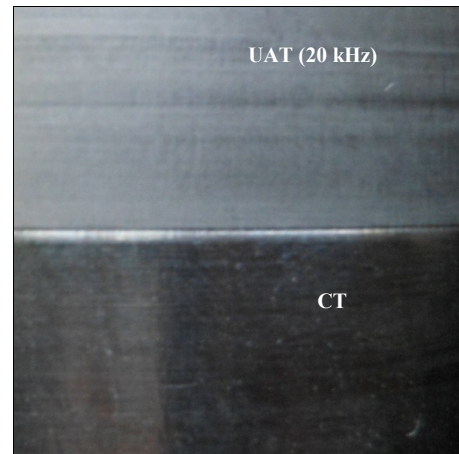


Fig.9a: Machined surfaces

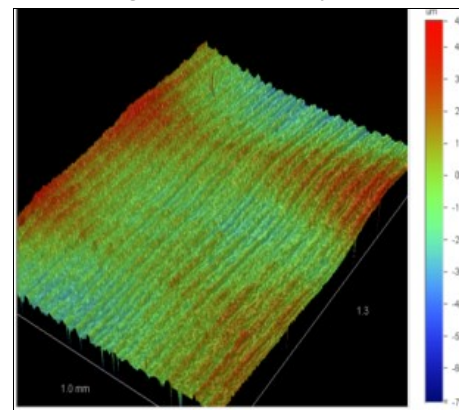


Fig.9b: 3D topography – CT

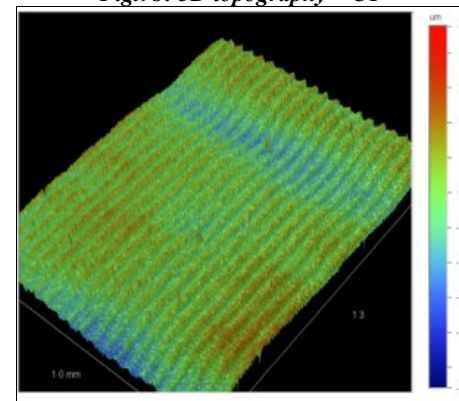


Fig.9c: 3D topography – UAT

Fig.9b-c: 3D Microtopography for the CTed and UATed chips

Fig. 9b-c shows the 3D micro-topography for both ultrasonic and conventional turned surface at the same cutting conditions. It is observed that the tool marks on the machined surfaces are on higher side during CT. However, the tool marks on UAT surfaces are smooth and much uniform. A reduction in contact time between the tool and work piece during UAT leads to a change in material deformation process [3]. This reduces the cutting temperature and tool wear, which

ultimately improves the surface quality of the deformed workpiece. The average surface roughness R_a value measured for CT surface is $1 \mu\text{m}$ and that for UAT surface it is $0.6 \mu\text{m}$ R_a . Thus, 40% reduction in surface roughness is observed on UAT surfaces than the CT surfaces. “Fig.10a-b” shows optical images of the CTed and UATed surface. During UAT process, material is removed such that it produces ‘fish scale’ like structure on the surface [6].

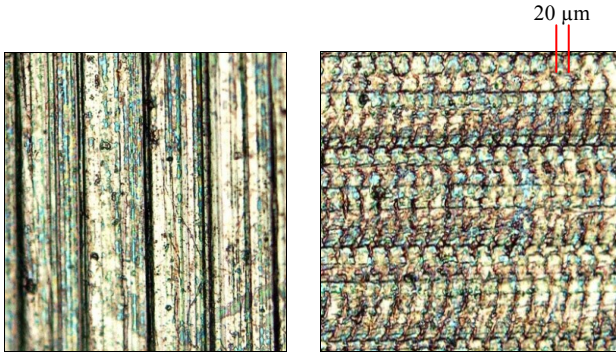


Fig.10a: CTed surface Fig.10b: UATed surface

Fig.10a-b: Optical images for CTed and UATed surfaces

E. CUTTING TEMPERATURE

One of the most important parameters in metal cutting is temperature in the cutting zones. An increase in cutting temperature can affect the cutting process in terms of thermal softening i.e. reduction in yield stress and other material properties such as Young’s modulus, coefficient of thermal expansion, specific heat and thermal conductivity, etc. The excessive heating can lead to the tool wear and a reduction in the tool life. During UAT, the cutting tool separates from the chip within each cycle of ultrasonic vibrations. Such intermittent contacts lead to a reduction in the total time for thermal conduction between the tool and chip and cooling due to convective heat transfer to the environment [7]. Measurement of cutting temperature was done during both CT and UAT processes by using a thermal imaging camera, FLIR P 640. “Fig.11a-b” shows the images captured by thermal imaging camera giving maximum machining temperature attained during 120 s of both UAT and CT.

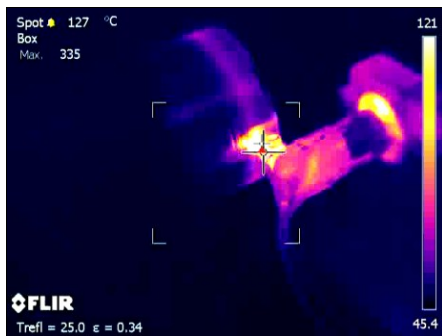


Fig.11a: UAT maximum temp



Fig.11b: CT maximum temp

Fig.11a-b: Thermal imaging camera images for maximum cutting temperature during UAT and CT (V_c -20 m/min, s -0.1 mm/rev, f -20 kHz, a -20 μm)

About 25% reduction in maximum temperature achieved at the chip tool interface is observed during UAT compared to that of during CT at a cutting speed of 20 m/min

F. CUTTING FORCES

Imposing ultrasonic vibrations on the cutting tool during conventional turning process leads to a reduction in cutting forces. This is due to a reduction in tool workpiece contact ratio (TWCR) [3]. Thus, the intermittent machining during UAT increases the non-cutting time of the tool, which decreases the cutting forces and enhances the tool life. In UAT, the vibrating tool causes the forces to fluctuate over a wide range hence, only the average values of cutting forces were used for comparison. The cutting forces were evaluated by measuring the deflection of cutting tool holder or horn using dial gauge of least count $1 \mu\text{m}$ in both cutting as well as in thrust directions.

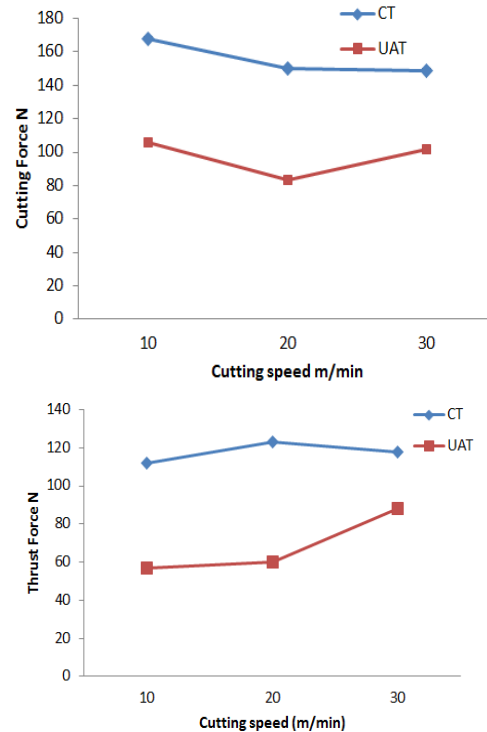


Fig.12: Effect of increase in cutting speed on cutting and thrust forces during UAT and CT

As shown in Fig. 12, about 44 % decrease in cutting forces, and 50 % decrease in thrust forces was observed during UAT as compared to the CT at a cutting speed of 20m/min.

CONCLUSIONS

Experimentally it has been seen that a significant effect of ultrasonic vibrations is evident on the microstructural aspects of chip formation in a turning operation. The UAT produces thin and continuous chips. However, CT produces thick and uneven chips. The less deformed grains on UAT machined surface indicates lower machined surface hardness. A reduction in cutting temperature generated during UAT reduces the intensity of thermal softening during UAT than that of in CT. Reduction in shear band formation and increase in shear angle during UAT indicates reduction in cutting forces than that of in CT. UAT generates matte finish on machined surface with lower average surface roughness (R_a) than that of during CT.

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