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Ultrasonically assisted machining of Titanium alloys

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In this chapter we discuss the nuances of a non-conventional machining technique known as ultrasonically assisted machining, which has been used to demonstrate tractable benefits in the machining of titanium alloys. We also demonstrate how further improvements may be achieved by combining this machining technique with the well known advantages of hot machining in metals and alloys.

1.1 Introduction

Recently, machinability of titanium alloys has been an important topic of research. Titanium poses unique machining challenges, primarily due to its low thermal conductivity, causing high temperatures in a process zone during cutting, and high chemical affinity to tool materials, which can lead to welding of Ti particles to tools, accelerating adhesion-based tool wear. Several studies demonstrated that the β phase of Ti is particularly challenging to machine; in fact, the material's heat treatment condition significantly affects the overall machinability [1].

Typically, this problem is addressed by two approaches: (1) imposing low cutting speeds (often less than 50 m/min) and feeds (typically, below 0.3mm/rev); (2) employing cutting fluids or coolants. The use of low cutting speeds inevitably lead to an increase in machining costs, especially when many aircraft components require almost 90% of a blank material to be removed to obtain a finished product. Additionally, for deeper cuts (i.e. high depths-of-cut magnitudes), a further lowering of cutting speeds is required. Thus, there is a clear need to increase material removal rates (MRRs) to improve machining economics. In recent years, machining costs involving the use of cutting fluids have increased substantially, primarily due to environmental concerns. The handling of cutting fluids as well as their eventual disposal must obey strict rules of environmental protection. As a result, the costs related to cutting fluids represent a large amount of the total machining costs, which may exceed the cost of cutting tools itself [2]. Consequently, elimination of cutting fluids, if possible, can be a significant economic incentive.

Thus, there is a need for alternate techniques in dry machining of Ti-alloys. This is a reason for a spate of research in hybrid approaches to machining, whereby two or more complementary cutting techniques or mechanisms are used simultaneously to achieve greater productivity or enhance product quality. Examples of such approaches are a combination of laser-assisted machining (LAM) and cryogenic cooling of the tool [3]; electrical discharge machining (EDM) in milling of Ti alloys [4] and combination of EDM with ultrasonic machining [5], to name a few. One promising hybrid machining technique, which is the subject of this chapter, is ultrasonically assisted machining (UAM) and its variants.

The working principle of UAM is based on subjecting a machining tool to two independent motions. The first is a driving motion, which shapes the work-piece in a conventional process. Next, high-frequency (ultrasonic) vibration of specific frequency and intensity in a defined direction is superimposed on the driving motion of the tool. Thus, UAM belongs to the general class of vibration machining; however, it exhibits unique characteristics, which will be the subject of discussion in the following sections.

In this chapter, two specific hybrid machining processes will be discussed. First, the use of ultrasonically assisted machining in turning of Ti-alloys will be described. This process is henceforth referred to as *ultrasonically assisted turning* (or UAT for short). Two case studies will be presented with two different Ti-alloys. Then, a variant of the UAT, in which hot machining is combined with it to yield further improvements, is discussed. This machining process is referred to as *hot ultrasonically assisted turning* (or HUAT for short).

1.2 Ultrasonically assisted machining

Vibration machining (VM) was developed in the fifties of the last century for machining of ceramics and other hard and brittle materials [6]. There was a widespread interest during the 1980s, with increased applications of ceramic materials in the industry. VM experiments with steel, glass and brittle ceramics confirmed that life of diamond tools could be extended with improvements in surface finish when compared to conventional machining [7]. Here, we make an important distinction from a traditional understanding of ultrasonic or vibration machining processes. Typically, ultrasonic machining is understood to be an abrasive process, in which material removal is purely mechanical. The process equipment consists of a vibrational horn (the sonotrode), a tool part, an abrasive paste (typically, with boron carbide particles), and the working material. During machining, the frequency is adjusted, so that the tool-sonotrode system resonates at around 20 kHz (thus making it ultrasonic); as a result, the abrasive particles suspended in slurry are propelled at the work surface, causing rapid erosion. In this sense, the abrasive paste ultimately ‘cuts’ the work-piece.

The ultrasonically assisted machining (UAM) process, which is the subject of this chapter, is a new hybrid machining process, which differs from a traditional understanding of ‘ultrasonic machining’. First, it is a dry machining process,

where no coolants or an abrasive paste is needed (though, a system with flood cooling can be used, if required). Next, the vibrating cutting tool interacts with the work-piece directly and cuts the material using a micro-chipping process. Kinematically, the system is different from that for a conventional machining process, as the cutting tool translates as in conventional machining but with superimposed vibro-impacts, leading to improved cutting conditions as will be demonstrated here. The advantages of this method are not *a priori* obvious, because machine-tool vibration (chatter) has to be vigorously suppressed in most cases. Interestingly, when an externally controlled vibration is imposed on a cutting tool, significant improvements in surface finish, noise and tool-wear reduction are observed. Prior studies of vibration machining have shown that, to achieve the maximum possible benefit from the vibratory cutting process, the vibration system needs to be tuned to resonance. One major complicating matter is that this resonance often depends non-linearly on the machining/processing parameters and the load experienced during the cutting process. These non-linear effects need to be accounted for in a robust design of control systems. A system with only frequency control is insufficient in achieving peak performance of an ultrasonic system and there is a need for autoresonant control systems in which the signal obtained from the performance sensor is fed to the transducer directly by means of a positive feedback which provides instant control of the mechatronic system [8].

In UAM several experimental studies have been carried out. The vast majority of reported results in UAM of Ti-alloys deals with the study of machinability of Ti-15-3-3-3, Ti-6246 and variants [9,10].

1.2.1 Experimental Setup

Experiments were carried out on a universal lathe adequately modified to accommodate an ultrasonic cutting head with flexibility of switching between conventional and ultrasonic cutting regimes during a single turning operation. It is to be noted that such a cutting head may also be installed on a CNC machine. In the recent past, commercial variants have also been launched by DMG-Mori Seiki.

In the setup used to perform all the relevant experiments, the cutting head was a standard Langevin-type piezoelectric ultrasonic transducer mounted on a waveguide with an aluminium concentrator, which amplifies the ultrasonic vibrations. A schematic of the ultrasonic cutting assembly is shown in Figure 1. The assembly was fixed to the cross slide of the lathe by a specially designed tool-post attachment (Figure 2). To record cutting forces during the machining process a dynamometer is attached to the cutting head. For analysis, the cutting force can be resolved into three orthonormal components in the x , y and z directions corresponding to the tangential, radial and feed directions, respectively (Figure 2). Here, the tangential force is traditionally referred to as the primary cutting force.

For all machining trials, a cemented-carbide turning tools (SECO: DNMG 150608 MF1 CP500) with a nose radius of 0.8 mm with a low-depth-of-cut/finishing chip breaker optimized for low feed rates was used. The tool material

has a tough micro-grain structure suitable for intermittent cutting. The tool was mounted orthogonal to the work-piece axis so that the effective rake angle was approximately 14° and a clearance angle 0° .

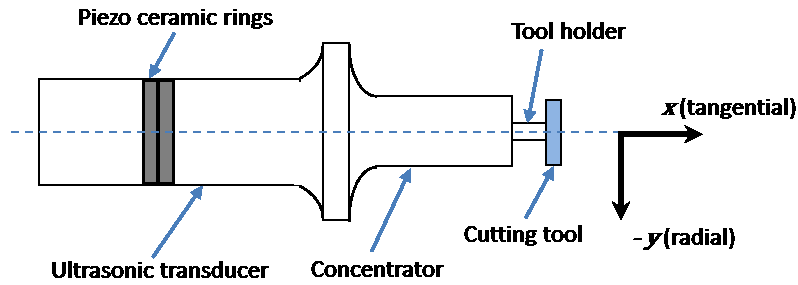


Figure 1. Schematic of ultrasonic cutting assembly (see also Fig. 2)

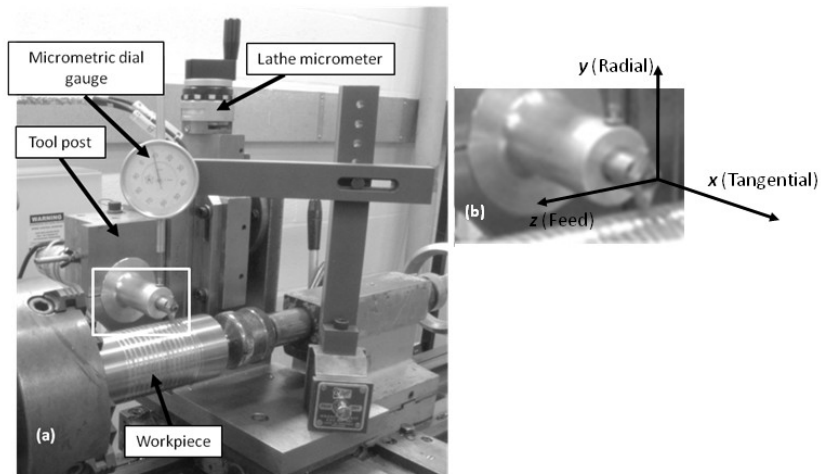


Figure 2. (a) Ultrasonic cutting assembly; (b) zoomed-in picture of cutting tool (marked with white box in (a)) showing axis alignment

1.2.2 Case study 1: Ti-15-3-3-3

1.2.2.1 Work-piece material

The work-piece material, designated as Ti-15-3-3-3, belongs to a group of meta-stable β -Ti alloys, demonstrating significant precipitation-hardening characteristics. The alloy was solution-treated and aged by annealing at 790°C for 30

minutes followed by air cooling, resulting in a β -phase state [9]. The Ti alloy was manufactured at the GfE-Metalle und Materialien GmbH in Nuremberg, Germany, as were all the other alloys described in case studies below.

1.2.2.2 Experimental Studies and Machining Results

Short experimental runs were conducted in our machining tests, in which conventional turning (CT) was immediately followed by UAT. Each experimental run was repeated 6 times to obtain reasonable statistics for our experimental data.

During vibration-assisted cutting it is important to monitor the cutting kinematics. To this end, a laser vibrometer was used to monitor cutting-tool vibration during the experiment. The cutting head demonstrated spurious vibrations in radial and axial directions with amplitudes of $\sim 1 \mu\text{m}$ and $\sim 0.3 \mu\text{m}$, respectively. This shows the difficulty to achieve a pure one-dimensional vibration system in transducer design and manufacture. Still, the vibratory amplitude in the primary cutting direction (tangential direction) was observed to be $10 \mu\text{m}$ for all the cutting depths, significantly dominating the overall cutting process. The cutting parameters used in the tests are listed in Table 1.

Table 1: Cutting parameters in experiments with Ti-15-3-3-3

Cutting speed, V (m/min)	10 - 70
Feed, f (mm/rev)	0.1
Depth of cut, a_p (μm)	50-500
Vibration frequency, f (kHz)	17.9
Tangential vibration amplitude, a (μm)	10
Coolant	None

Superimposing ultrasonic vibration on the cutting tool is known to improve the surface finish of both ductile brittle materials, with a concomitant reduction in cutting forces and machine chatter. It should be noted that imposing tangential vibration (Fig. 2) on the cutting tool in UAT changes the nature of the tool-work-piece interaction to an intermittent dynamic contact. From a 1-D analysis of such interaction, a relation between the critical oscillatory speed of the tool (v_c) and the speed of the work-piece motion (V) can be derived for the UAT process to be effective:

$$v_c > V. \quad (1)$$

The critical tool speed and the cutting speed are related to the machining parameters [8] by

$$v_c = 2\pi af \quad (2)$$

$$V = \pi nD, \quad (3)$$

where n is the rotational speed of the lathe, D is the diameter of the machined work-piece, and a and f are the amplitude and frequency of the imposed vibration, respectively. For the machining parameters used, $v_c = 67 \text{ m/min}$. It is expected that

condition $v_c > V$ will ensure tool separation from the work-piece in each vibratory cycle.

1.2.2.3 Results: Cutting Forces

Cutting forces imposed on the tool were measured for CT and UAT performed with a varying depth of cut (a_p). The magnitudes of depths of cuts ranging from 50 μm to 500 μm were set with varying increments of 50 μm and 100 μm . A relatively low feed rate of 0.1 mm/rev was set to emulate high-precision machining, which typically deals with low material-removal rates (MRR) and, consequently, low feed rates. The raw data acquired with the dynamometer via an attached picoscope, was processed in Matlab, without any filtering, to obtain average cutting forces. In the analysis, data from the initial engagement was eliminated (see Fig. 3).

In all the experiments conducted, the axial/feed force component was measurably smaller than the primary tangential cutting force (Fig. 3 shows a typical force measurement from our experimental procedure). This is due to the low imposed feed rate coupled with a large nose radius operating at low depth of cuts. The measured cutting force components at different levels of a_p for both CT and UAT are presented in Figure 4. The axial force component did not change significantly (Fig. 3) and thus was not used in the further analysis. The data in Fig. 4 presents average values obtained from multiple machining runs, and the error bars indicate the standard deviation of the measured forces. Significant force reductions (typically 75%) in the primary and radial cutting direction in UAT are observed for the entire studied range of a_p . Improvements in the tangential cutting forces are expected in vibration-assisted turning as these correspond to the primary direction (along the x -axis) of ultrasonic vibration imposed on the cutting tool. Interestingly, high-frequency, low-amplitude vibration in the radial direction had also a noticeable effect on the measured cutting-force components. This is due to geometric reasons, since the curvature of the work-piece allows for tool separation in the radial direction, especially for small a_p . It is interesting to note that the average cutting forces in UAT for $a_p = 500 \mu\text{m}$ are comparable to those in CT for $a_p = 150 \mu\text{m}$ (see Fig. 4). This implies that, tool wear and tool life remaining the same in UAT, the MRR during vibration-assisted machining can be potentially increased by a factor >3 (owing to the diamond-shaped cutting tool geometry), with the cutting tool being exposed to the same level of cutting forces for these cutting depths. This hypothesis needs to be analysed in detail in the future.

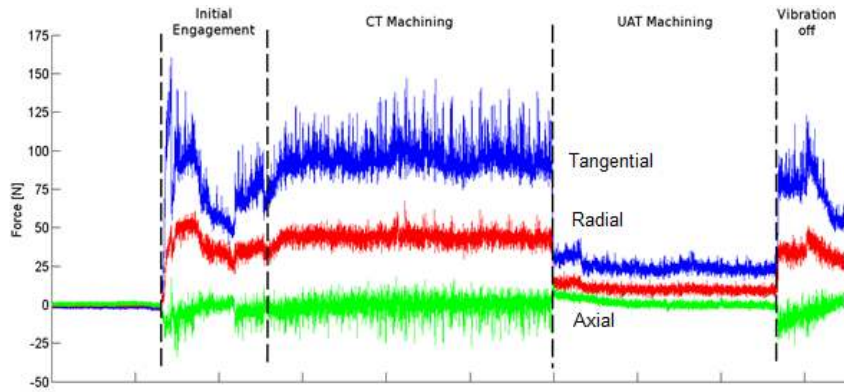


Figure 3. Evolution of force-component signals produced by dynamometer in single run. Machining parameters used: $V = 10$ m/min, $a_p = 300$ μm , $f = 0.1$ mm/rev. In UAT: $f = 17.9$ kHz, $a = 10$ μm .

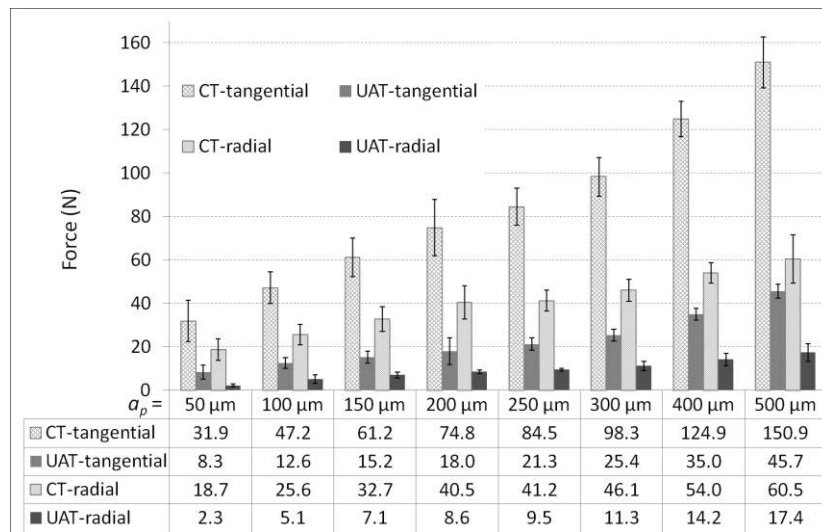


Figure 4. Cutting forces for CT and UAT at various depths of cut

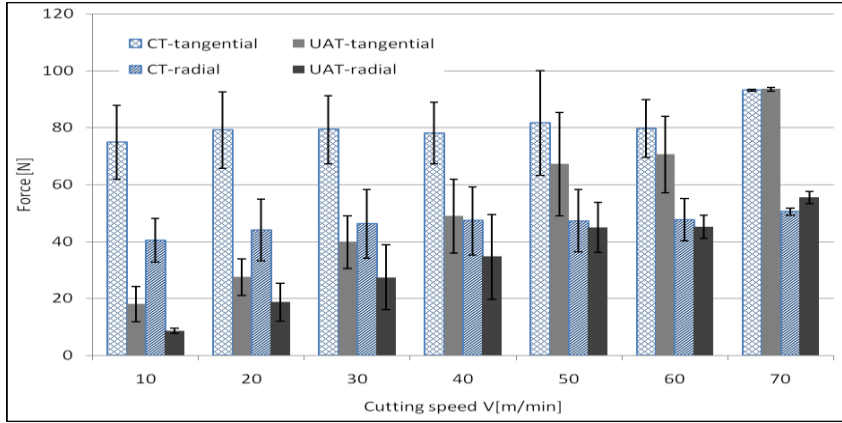


Figure 5. Cutting forces for $a_p = 200 \mu\text{m}$ in CT and UAT at various cutting speeds

Next, the effect of cutting speed on machining thrust forces was investigated. Figure 5 shows the measured forces in CT and UAT averaged over 5 experimental runs for each value of the used cutting speed. The cutting forces in CT show low sensitivity to the cutting speed within the studied range, as expected. However, in UAT, cutting forces increased with the increasing cutting speed, indicating that the derived relation (1) holds. In other words, with increasing speed, the tool separation in each vibro-impact reduces with a complete loss of separation at speeds exceeding v_c .

1.2.2.4 Results: Surface Topography

Characterisation of surface topography of the finished work-piece are presented for $a_p = 200 \mu\text{m}$ and $V = 10 \text{ m/min}$. Figure 6 compares the texture of typical surfaces machined with CT and UAT (presented as 2D field plots). Distinct periodicity can be observed for the conventionally turned surface whereas for the enhanced machining technique this regularity is somewhat curtailed. In CT, the direction of tool path during machining is evident, with a periodicity of some $100 \mu\text{m}$, corresponding to the used feed rate of 0.1 mm/rev (Table 1). The machined surface profiles were analysed employing various texture parameters. Amplitude parameters calculated from the roughness profile, such as R_a , show a reduction of 49% in UAT when compared to CT. This implies that within the measured sampling lengths the average roughness is significantly lower in UAT: the multiple cycles of reversed toll motion in UAT have a polishing effect on the machined work-piece surface.

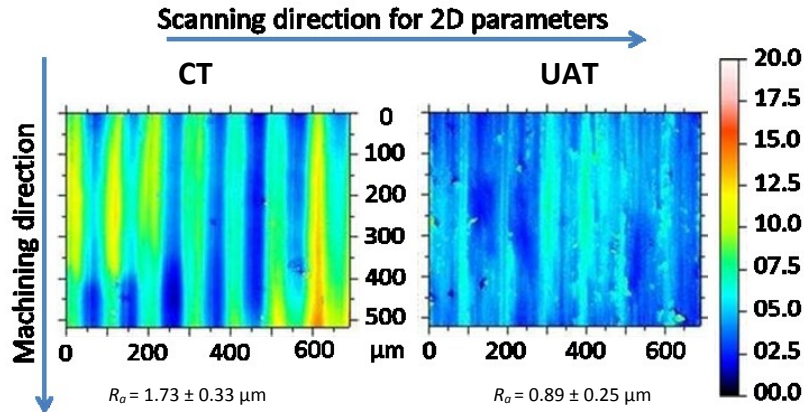


Figure 6. Interferometry scan on area of $0.53 \text{ mm} \times 0.7 \text{ mm}$ of surfaces machined with CT and UAT for $a_p = 200 \text{ }\mu\text{m}$ and $V = 10 \text{ m/min}$.

1.2.2.5 Results: Sub-surface Analysis

Conventional machining leads to high temperatures in the process zone and at the tool-work-piece interface. Coupled with low thermal conductivity of the β -Ti alloy under study, it was imperative to check a sub-surface layer of the work-piece for phase transformations. Usually, high temperatures in β -Ti alloys lead to formation of α -Ti phases that appear as needle-like structures under microscope. These phases are particularly undesirable as they compromise the improved mechanical characteristics of the β phase.

Sub-surface layers of work-pieces obtained with UAT and CT for machining conditions corresponding to $a_p = 500 \text{ }\mu\text{m}$ were analysed. Figure 7 compares the sub-surface microstructures for these two techniques. The alloy presents a coarse-grain structure with grains averaging $100 \text{ }\mu\text{m}$ in size. The images show no needle-like (α -Ti) features and no visible changes in the grain size for both UAT and CT when compared to a virgin work-piece sample (i.e. prior to machining (Fig. 7a)). Since no visible changes were observed in the UAT work-piece (Fig. 7), it is safe to claim that no phase transformations are expected at the studied depths of cuts and cutting speeds.

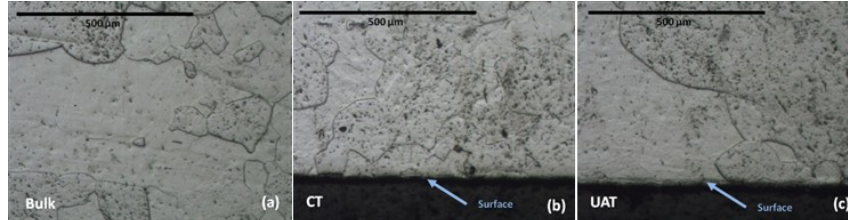


Figure 7. Etched cross sections of work-pieces: (a) virgin-state bulk sample; (b) machined with CT for $a_p = 500 \mu\text{m}$; (c) machined with UAT for $a_p = 500 \mu\text{m}$.

1.2.3 Case study 2: Ti-6-2-4-6

1.2.3.1 Work-piece Material

The second work-piece material, Ti-6246, was also produced by the GfE-Metalle und Materialien GmbH in Nuremberg, Germany. After 2x vacuum arc remelting, the alloy was forged in the two-phase field followed by air cooling, stress-relief annealing and stripping. Next, the alloy was re-melted once in a plasma-beam cold hearth melter followed by casting and stress-relief annealing. Microstructure studies revealed that the average grain size in the alloy was $147 \pm 13 \mu\text{m}$ [10].

1.2.3.2 Experimental Studies and Machining Results

Short machining runs were conducted in the experimental study. The machining parameters of these runs are listed in Table 2

Table 2. Cutting conditions used in experiments with Ti-6246

Parameters	Magnitude
Cutting speed, V (m/min)	10; 30; 60
Depth of cut, a_p (μm)	200
Feed rate, f_r (mm/rev)	0.1
Vibration frequency in UAT, f (kHz)	20
Vibration amplitude in UAT, a (μm)	10

1.2.3.3 Results: Cutting Forces

Application of ultrasonic vibration to the cutting tool brought a noticeable reduction in the cutting forces (Fig 8). A significant reduction (74%) in tangential component of the cutting forces was observed for application of vibration at the cutting speed of 10 m/min. There was also a considerable reduction (59%) in the radial component of the cutting force at the same speed. The level of both cutting forces (the tangential and the radial) was slightly reduced with an increase in the cutting speed in CT in Ti-6246 (Fig. 8) (when compared to the cutting forces at 10 m/min). This effect was not visible in Ti-15-3-3-3. In UAT at $v = 30$ m/min, the reduction in the tangential and radial force components was observed to be 51% and 21%, respectively. Consequently, at a higher cutting speed of 60 m/min, the reduction in tangential force component was 21% with hardly any reduction in the radial force component. It should be noted that the critical velocity was ~ 75 m/min.

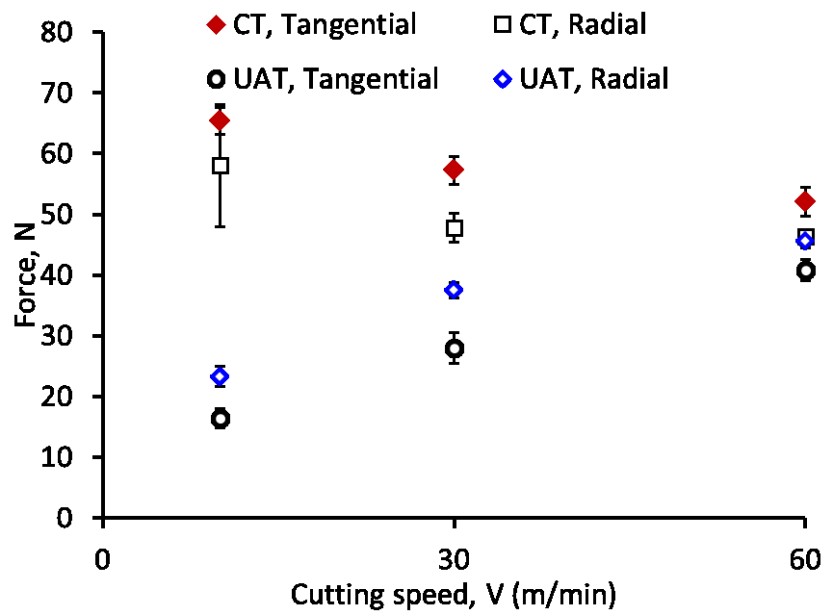


Figure 8. Cutting forces in CT and UAT of Ti-6246 at $a_p = 200 \mu\text{m}$ for various cutting speeds

1.2.3.4 Results: Surface Topography

As before, UAT shows an improved surface quality in the machined work-piece (Fig. 9). The level of R_a for $V = 10$ m/min in CT was measured to be 0.82 ± 0.20 μm while for UAT it was 0.37 ± 0.04 μm . Thus, a significant improvement exceeding 50% was observed in UAT when compared to CT. Similar reductions were also measured when machining at $V = 30$ m/min.

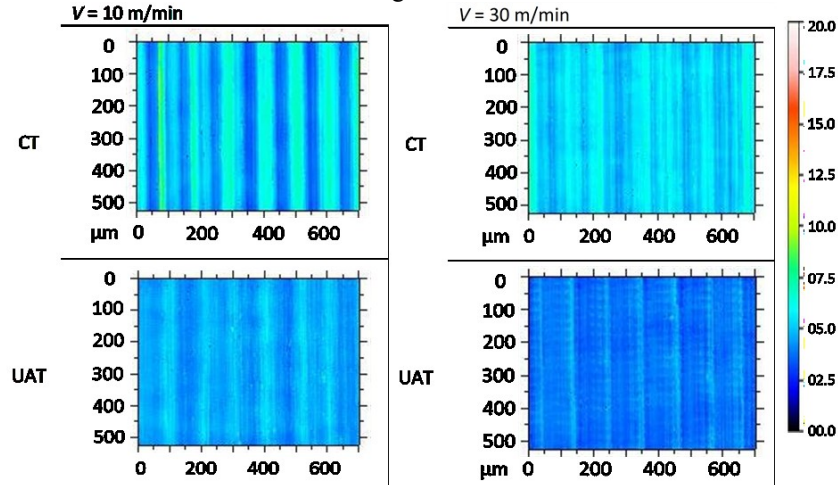


Figure 9. Surface profile scan for CT and UAT at various cutting speeds at $a_p = 200$ μm

1.2.4 Discussion

The two case studies presented demonstrate that UAT shows systemic improvements in machining the Ti-alloys in general, with a significant measurable reduction in machining forces with an improved surface topography of the machined work-piece. Studies also indicate that UAT does not lead to any noticeable detrimental effects such as grain growth, re-crystallisation in machined work-piece.

1.3 HUAT

In this section, a new hybrid machining process is discussed that combines the advantages of UAT with the well-documented effects of hot machining in metals and alloys [11]. The experimental setup discussed in Section 1.2 was modified to house a band resistance heater around the cylindrical work-piece (Fig. 10).

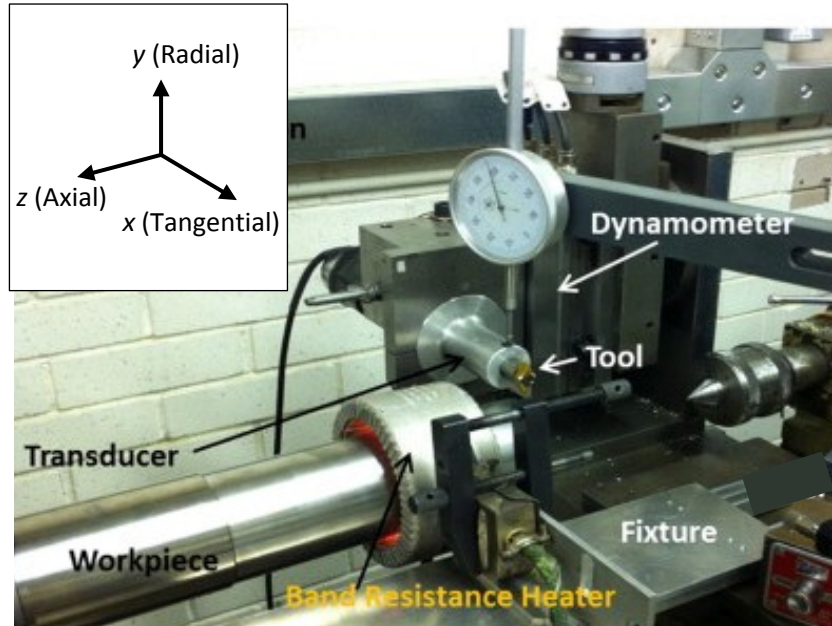


Figure 10. Experimental setup in hot ultrasonically assisted turning

1.3.1 Experimental Setup and Methodology

For hot-machining tests, a band-resistance heater, encircling the work-piece, was used as a heat source to increase the temperature of the work-piece to $300 \pm 10^\circ\text{C}$. Thermal measurements were performed using a Teflon-coated K-type thermocouple with a maximum measuring range of 1200°C in conjunction with a thermal camera (FLIR ThermoCAMTM SC3000) in real-time.

The Ti alloy used was the β Ti alloy, Ti15-3-3-3, used in Case study 1; this allows for a realistic comparison with UAT.

1.3.2 Experimental Studies and Machining Results

Hot machining was carried out at an elevated temperature of 300°C , i.e. the work-piece was pre-heated before the machining process. Next, the band resistance heater was removed. The temperature at the work-piece surface was monitored continuously. Each experimental test lasted for approximately 90 seconds. Within the first 20 seconds the depth of cut was set to the desired magnitude followed by hot conventional turning (HCT) for 20 seconds. Next, ultrasonic vibration was switched on for approximately 40 seconds of the HUAT regime before being switched off to recover the HCT cutting conditions. Each experiment was

repeated at least five times to obtain reasonable statistics on the experimental data. The machining parameters used in the tests are listed in Table 3.

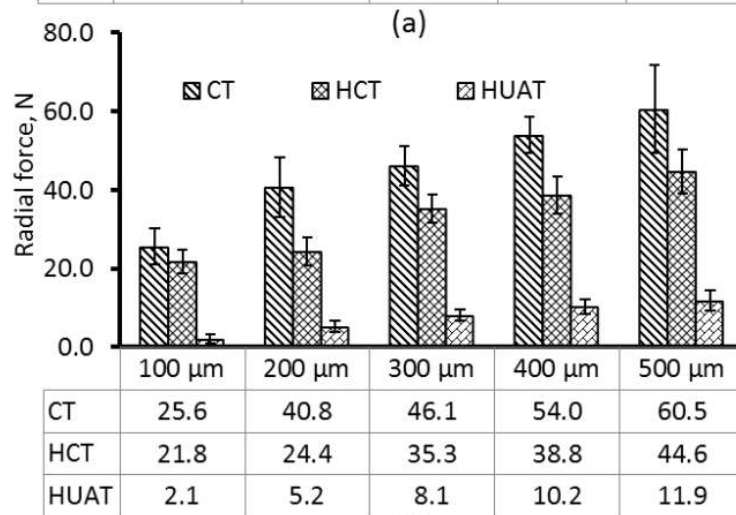
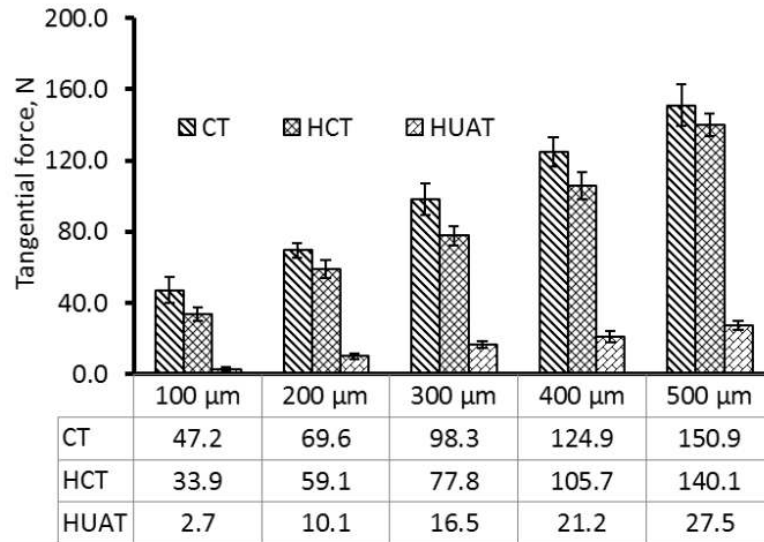
Table 3: Cutting parameters in HUAT

Cutting speed, V (m/min)	10
Feed, f (mm/rev)	0.1
Depth of cut, a_p (μm)	100-500
Vibration frequency, f (kHz)	20
Tangential vibration amplitude, a (μm)	8
In HCT and HUAT: Work-piece temperature, T ($^{\circ}\text{C}$)	300, 500

1.3.3 Results: Measurements of Cutting Forces and Temperature

Cutting forces were measured in real-time during the machining operation for various depths of cut (a_p). A substantial reduction in tangential and radial components of forces was observed in turning of Ti-15-3-3-3 using HUAT when compared to conventional machining conditions, as reported for Case study 1 (Fig. 11). At $a_p=100 \mu\text{m}$, the reduction in tangential and radial components of cutting forces was approximately 95% in HUAT when compared to CT. The decline in cutting forces reduces with an increase in the depth of cut and, ultimately, a uniform reduction of 80-85% was observed in HUAT $a_p > 200 \mu\text{m}$. On the other hand, a reduction of some 20% in cutting forces can be achieved in HCT. In hot machining, the reduction in the cutting forces is mainly attributed to the decrease in yield strength of the alloy at elevated temperature. However, in HUAT, thermal softening when combined with tool separation in each vibratory cycle of tool movement resulted in a significantly higher force reduction compared to that for other machining processes.

Experiments were carried out to track the process-zone temperature in HCT and HUAT. The temperature measurement at the process zone in CT was also conducted during Case study 1, the results will be reported here for comparison. The temperature of the cutting region in HCT (where the work-piece was heated to 300°C before machining) at $a_p=300 \mu\text{m}$, was approximately 250°C higher when compared to that in conventional turning, whereas in HUAT the temperature was some 300°C higher (Fig. 12). The temperature increase at the process zone with time was observed to be gradual after the initial engagement of the tool. In HUAT, a higher temperature in the process zone was observed when compared to HCT. This is attributed to the temperature rise due to energy dissipation from vibro-impacts imposed on the work-piece via the cutting tool in ultrasonic machining.



(b)

Figure 11. Cutting forces at various depths of cut and $V = 10$ m/min; Hot machining at 300°C . (a) Tangential force (b) Radial force.

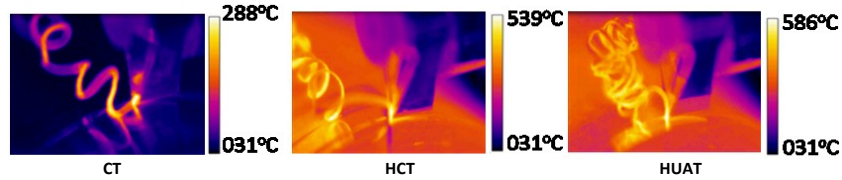


Figure 12. Temperature of process zone in CT, HCT and HUAT

1.3.4 Results: Surface Topography

In this part of our study, surface roughness of the machined work-piece was analysed for CT, HCT and HUAT at $a_p = 300 \mu\text{m}$. A significant reduction in the roughness parameter (R_a) was observed in HUAT and HCT, when compared to CT (Fig. 13). In HUAT and HCT, an improvement in excess of 50% was observed. Figure 13 compares the texture of typical surfaces machined with different techniques (presented as 2D field plots). Distinct periodicity can be observed for the conventionally turned surface whereas for the enhanced machining techniques this regularity is somewhat reduced. The surface quality in HCT and HUAT was effectively the same in statistical terms.

1.3.5 Discussion

It is known that needle-like precipitate appear on the surface of Ti alloys when subjected to temperatures above 450°C for more than one hour. The specimens' machined with HUAT were investigated at different magnifications, and no signs of oxidation or metallurgical changes were observed. It should be noted that, though the temperature in the process zone was observed to be higher than 450°C in HUAT and HCT, it did not show any detrimental effect on material's characteristics due to the short exposure time to high temperatures (in comparison to the mentioned 1 hour). As a result, no precipitates were observed to form on the machined surface. The experiments indicate that it is possible to achieve cutting force reductions in excess of 80–85% – when compared to conventional machining techniques – with an improved surface roughness of the machined work-piece material.

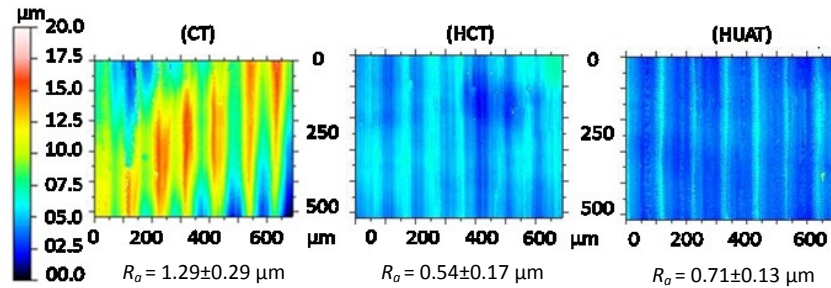


Figure 13. Surface profile scan for different machining techniques at $V = 10 \text{ m/min}$, $a_p = 300 \text{ }\mu\text{m}$

1.4 Conclusions and outlook

Here, the advantages of using hybrid machining techniques, employed to improve substantially machining of Ti-alloys, were discussed. The machining processes do not require any coolants, and have been shown to improve the topography of the machined surface with a significant reduction in machining forces. There is indeed a potential to increase MRR in ultrasonically assisted machining by several times.

However, there is a further need for research. First, advanced tools for ultrasonically assisted machining would benefit these techniques. The use of conventional tools in a vibro-impact machining process is not ideal; thus, tool manufacturers need to investigate innovative tool geometry as well as tool materials and coating for UAM. Next, there is a need to understand the nature of the ultrasonic softening effect in alloys, if any. Finally, more research is required in developing next generation auto-resonant control systems, which will allow for widespread industrial applications and use of UAM.

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