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Ultrasonically assisted turning of Ti-6Al-2Sn-4Zr-6Mo

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Abstract. Titanium alloys are widely used in the aerospace and offshore industries due to their high strength-to-weight ratio sustained at elevated temperatures, their fracture-resistance features and exceptionally good corrosion-resistance properties. However, poor thermal conductivity and high chemical affinity of these alloys to tool materials severely impair their machinability. As a result the machining processes of titanium alloys are typically characterized by low cutting feeds and speeds making production of components uneconomical.

Recently, a non-conventional hybrid machining technique, namely, ultrasonically assisted turning has been shown to significantly improve the machinability of intractable alloys with a concomitant improvement in material removal rates, thus improving machining economics.

In the current work, a 3D finite element model of turning of Ti-6Al-2Sn-4Zr-6Mo is developed in the commercial software, MSC Marc/Mentat. A constitutive behaviour of the workpiece material under large deformations and elevated temperatures is adequately represented by a Johnson-Cook material model. For validation of the developed numerical model, experimental tests were carried out. The numerical and experimental results were found to be in good agreement.

1. Introduction

Titanium alloys are extensively used in the aerospace, marine, medical and chemical processing industries owing to their exceptional corrosion-resistance, high-strength and light weight. However, their low thermal conductivity and high-strength severely impair the machinability of these alloys with conventional machining operations [1]. High cutting forces and high temperature at the tool-workpiece interface zone lead to premature tool failure, increasing manufacturing costs. In recent years, costs of machining involving the use of cutting fluids have increased substantially, primarily due to environmental concerns: the handling of cutting fluids as well as their disposal must obey strict rules of environmental protection. For manufacturing companies, the costs related to cutting fluids represent a large amount of the total machining costs. Consequently, elimination of cutting fluids, if possible, can be a significant economic incentive. Thus, dry machining attracts now great interest since it addresses current needs for environmentally friendly manufacturing.

Therefore, new hybrid-machining techniques are needed to improve the overall machinability of these high-strength alloys. Ultrasonically assisted turning (UAT) is a novel machining technique, in which high-frequency vibrations are superimposed on a cutting tool, preferably in a primary cutting direction, to improve the machinability of those high-strength alloys (Fig. 1). UAT has shown significant improvement in the processing of Ti-15333 [2] and Inconel 718 [3, 4].

Experimental observations indicate that various machining parameters, such as vibration frequency and amplitude, tool geometry and overall cutting speed, significantly affect the quality of machining in UAT. Numerical simulations based on finite-element analysis can be used to quantify the observed effects and to study various underlying physical characteristics of the turning of advanced materials with a vibrating tool.

The aim of the current study is to investigate the effect of ultrasonic vibration on machining cutting forces and temperature at the cutting region in turning of Ti-6Al-2Sn-4Zr-6Mo (a shorter notation – Ti-6246 – is used below). The current work elucidates the advantages of UAT in the processing of Ti-6246.

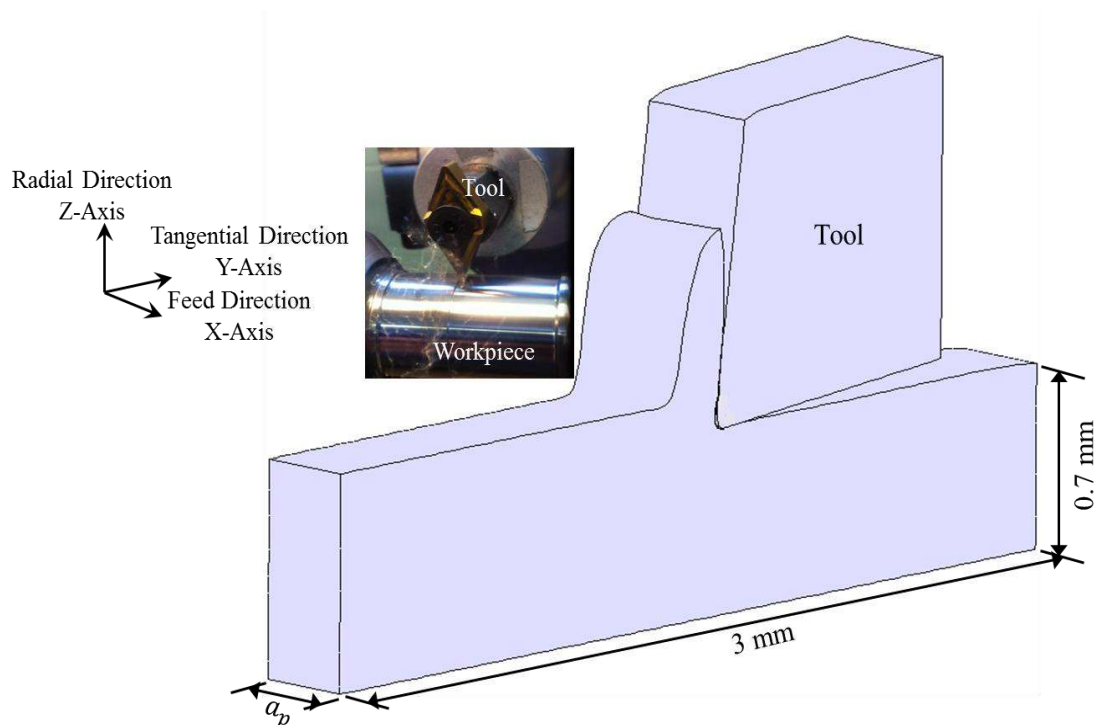


Figure 1: Schematic diagram of cutting model and principal direction of vibration

2. Experimental setup

A current UAT setup used in machining experiments consisted of a modified Harrison 300 lathe, with a custom-built ultrasonic transducer mounted on a wave-guide, a force-measurement and data acquisition systems, a charge amplifier and an A/D converter. The cutting-force components were measured with a Kistler piezoelectric dynamometer (KIAG SWISS Type 9257A), mounted on the cross slide of the lathe using a custom-built tool post. The ultrasonic transducer was mounted on the dynamometer with adequate insulation to protect it from electrical disturbances, generated during machining operations. Additionally, a micrometric dial gauge was used to ensure an accurate depth of cut.

An ingot of $\alpha+\beta$ -Ti-based alloy Ti-6246 was used as a workpiece material, and a commercial tungsten carbide insert, PVD coated with TiN (DNMG-150608 supplied by Seco) was employed as a cutting tool. All experiments were carried out in dry-cutting conditions without the use of any lubricants or coolants.

Several tests for conventional turning (CT) and UAT were carried out, and the primary cutting force in the tangential direction (see Fig. 1) was measured. Each experiment was repeated at least five times to get statistically consistent data. The cutting forces reduce significantly during ultrasonically assisted operations when compared to those obtained in CT. In addition to force reduction other substantial benefits were observed, in particular, elimination of the chatter noise during operations and better surface finish in the machined workpiece [4-6]. Furthermore, a FLIR ThermoCAM™ SC3000 camera was used to carry out thermal analysis in real time during the cutting operation. The system consists of

a built in 20° lens, cables, connectors and range of optional hardware and software accessories. The new Stirling-cooled Quantum Well Infrared Photon (QWIP) photo-detector enables the system to capture images with a spectral response between 8 and 9 μm , temperature range of -20°C to 2000°C , 320×240 pixel resolution, low noise detection and high image stability and uniformity. In the current experiments, a temperature resolution of 30°C to 650°C was used. The ThermoCAM® QuickView™ software was used to analyse the data of the FLIR ThermoCAM™ SC3000 system.

3. Model and Simulations

A schematic of the workpiece and the cutting tool is shown in Fig. 1. The deformable workpiece had the following dimensions: 3.0 mm in length and 0.7 mm in height. Initially, the workpiece was meshed with 8-noded iso-parametric elements with a minimum element length of 0.1 mm; they were further converted to 5-noded tetrahedron elements as a result of re-meshing of the highly distorted areas [7]. The tool was meshed using 2500 four-noded iso-parametric quadrilateral elements with a refined mesh close to the cutting edge. In order to simulate UAT, harmonic oscillations in the cutting direction (tangential direction) with an amplitude (a) and frequency (f) were superimposed on the cutting tool's movement. The cutting conditions and parameters of tool geometry used in the implicit FE simulations are summarized in Table 1.

The chip-formation process involves substantial plastic deformation in the workpiece material, especially near the cutting tip [8]. As a result, the elements near the cutting tip distort substantially, leading to numerical convergence problems in simulations. The use of the re-meshing techniques helps to mitigate problems with convergence as highly distorted elements are replaced with geometrically consistent ones.

The ambient temperature was selected as 20°C for the numerical experiments. Additionally, the effect of friction on the tool-workpiece-interface was also accounted for [9, 10]. This was achieved by choosing a friction coefficient as shown in Table 1; $m_{fr} = 0.5$ corresponds to the dry cutting condition (without any lubricant). The number of simulation steps was kept at 5000 with a total simulated period of time of 0.0179 s.

Table 1: Cutting parameters used in FE simulations

Parameters	Value
Cutting speed, V (m/min)	10
Depth of cut, a_p (mm)	0.3
Cutting edge radius, r (μm)	25
Rake angle α , (degree)	15
Frequency, f (kHz)	5; 10; 15; 17.8; 20; 25
Amplitude, a (μm)	3; 6; 8; 10; 12
Coefficient of friction, m_{fr}	0.5 (dry cutting)

3.1. Material Model

Strain, strain rate, temperature and strain hardening have a major influence on the flow stress or instantaneous yield strength, at which the material starts to deform plastically or flow. Accurate and reliable flow stress models are necessary to represent a constitutive behaviour of the workpiece material under different cutting conditions. In the current study, the Johnson-Cook material model [11] was used to describe the mechanical behaviour of alloy Ti-6246 at high-strain, high strain-rate and elevated temperature. The effects of strain, strain-rate and strain-hardening are combined in a multiplicative manner:

$$\sigma_y = [A + B(\epsilon_p)^n][1 + C \ln(\dot{\epsilon})][1 - (T_H)^m], \tag{1}$$

where σ_y is flow stress, ϵ_p is the effective plastic strain, $\dot{\epsilon} = \frac{\dot{\epsilon}_p}{\dot{\epsilon}_o}$ is the strain rate, $\dot{\epsilon}_p$ is the plastic strain rate, $\dot{\epsilon}_o$ is the reference strain rate, $T_H = \frac{T - T_R}{T_M - T_R}$ is the homologous temperature, T is the absolute temperature, T_M is the melting temperature, T_R is the room temperature, A is the initial yield stress at the reference strain rate, B is the hardening modulus, C is the strain rate-sensitivity coefficient, n is the hardening coefficient and m is the thermal softening coefficient. All these parameters were determined experimentally in a series of split-Hopkinson tests at Tampere University of Technology, Finland, and are given in Table 2.

Table 2: Johnson Cook Parameters of Ti-6246

Material	A (MPa)	B (MPa)	C	n	m	$\dot{\epsilon}_o$ (s ⁻¹)	T_M (°C)	T_R (°C)
Ti-6246	1657	402	0.0054	0.218	0.8034	1	1625	20

4. Discussion and Analysis of Results

The effect of vibration parameters on the tangential cutting forces produced in the turning of Ti-6246 is discussed here. In conventional turning (CT), the tool is in contact with the workpiece throughout the turning operation, resulted a peak force of 119 N. However, in UAT the tool separates from the workpiece and fully engages in each vibratory cycle, which leads to a fluctuating cutting force, changing from zero to a peak value of 123 N, results an average cutting force of 38 N. The reduction in average cutting forces is attributed to a vibro-impact mechanism of the tool interaction with the workpiece material. Figure 2 demonstrates the tangential components of cutting force for both CT and UAT for a frequency of 20 kHz and an amplitude of 8 μm, both experimentally and numerically. A significant reduction of 67% in tangential force was observed when compared to CT. The FE simulations for various depths of cut and cutting speed for both CT and UAT were carried out and were in good agreement with experimentation [6].

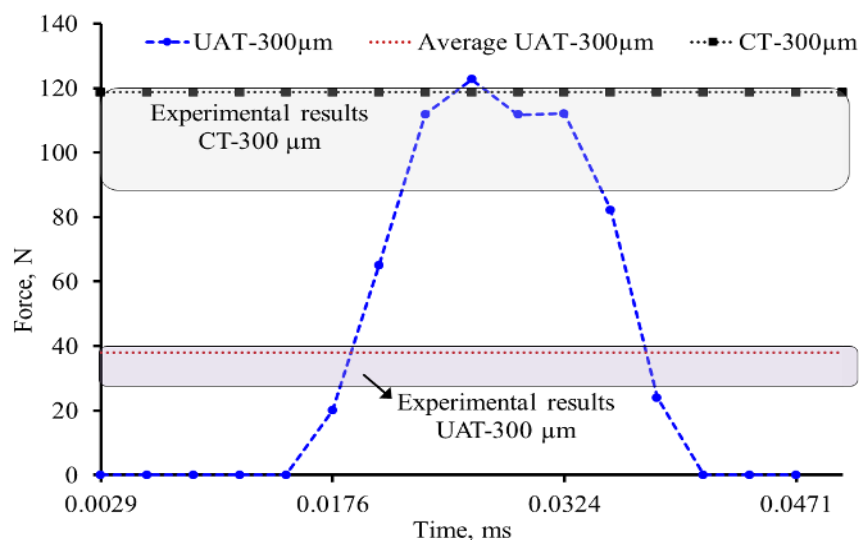


Figure 2: Comparison of forces in CT and UAT in dry cutting of Ti alloy ($f = 20$ kHz and $a = 8$ μm)

4.1. Effect of Vibration Amplitude

In UAT, the effects of amplitude on the average tangential cutting force were studied. The cutting depth was fixed at 300 μm , the feed rate at 100 μm and the amplitude changed from 3 μm to 12 μm . From Fig. 3, it is clear that the tangential component of force declines with an increase in vibration amplitude. It is observed that a higher vibration amplitude leads to an increase in the force reduction when compared to CT at the same machining parameters. However, high-power transducers are required to produce a stable high amplitude for UAT. A decrease of 41% in the average force level was recorded for an increase in the amplitude from 0 to 6 μm . A further 18% decrease was observed when the amplitude increased from 6 μm to 8 μm (Fig. 3). However, the reduction in cutting forces lessened above 8 μm (approx. 13% from 8 μm to 10 μm and ultimately 8% when increase from 10 μm to 12 μm). Therefore, in the current study, the amplitude of 8 μm was used in experimental analysis, resulting in a significant reduction in cutting forces.

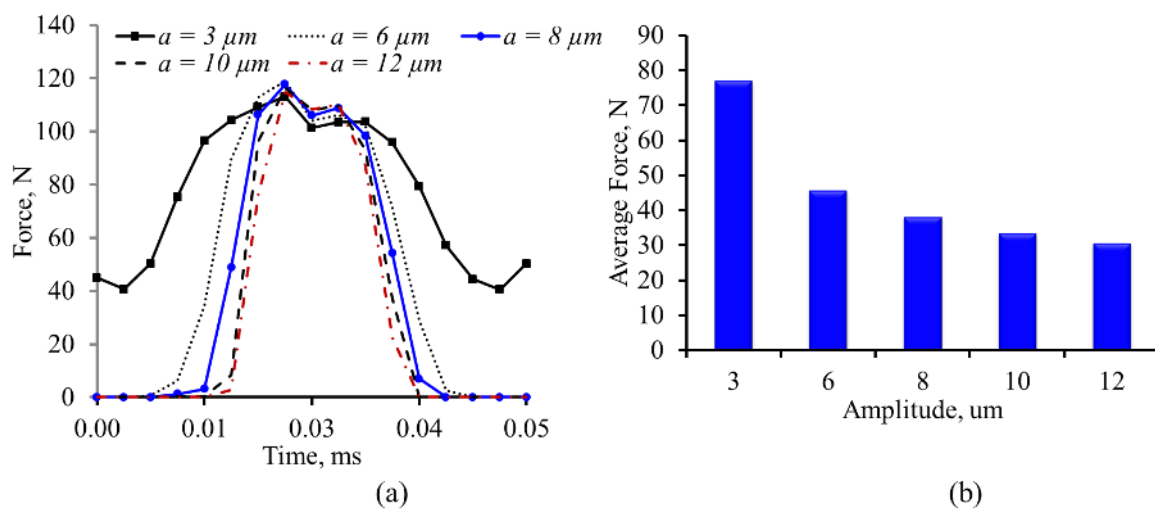


Figure 3: (a) Tangential cutting forces in UAT of Ti alloy; (b) Average cutting forces (variable amplitude; frequency 20 kHz)

4.2. Effect of Vibration Frequency

Five levels of frequency (5 kHz, 10 kHz, 15 kHz, 20 kHz and 25 kHz) were analysed in FE simulations of UAT of Ti-6246. In all the cases, the depth of cut was fixed at 300 μm , cutting speed at 10 m/min and amplitude of vibration at 8 μm . The relative velocity of the cutting tool is proportional to the vibrational amplitude and frequency:

$$V_t = a \sin(2\pi f t), \quad (2)$$

where f is the frequency, V_t is the cutting speed and a is the amplitude.

Equation (2) was verified by using the above set of frequencies to demonstrate the predictability of the model. For all five cases, a reduction in cutting forces with an increase in frequency is summarised in Fig. 4. An average reduction of 11 N in the cutting forces was noted with application of 5 kHz frequency on the cutting tool. The decline increases to 42 N and 52 N with an increase in frequency to 10 kHz and 15 kHz, respectively, when compared to CT. A further increase in frequency from 20 kHz to 25 kHz, resulted in average reduction of 56 N and 58 N when compared to CT, respectively. Therefore, in the current study, a frequency of 20 kHz was used for UAT.

4.3. Temperature Distribution

Temperature in the process zone generated in CT and UAT was investigated with the developed FE model. In all the cases, the depth of cut was fixed to 300 μm and cutting speed at 10 m/min. The temperature in UAT in both simulation and experimentation is approximately 200°C higher when

compared to CT in turning of Ti-6246, the possible cause for this is the effect of the additional factors linked to dissipation of the vibration energy [12]. Figure 5 shows the temperature distribution in the cutting region in CT and UAT. In the previous study of Ti-15333 and Inconel-718, the temperature in the process zone was 60-80°C higher when compared to CT [2, 4]. However, in the current study, a relatively higher temperature of the process zone was observed in UAT when compared to CT. Simulation results are in good qualitative agreement with the experimental ones.

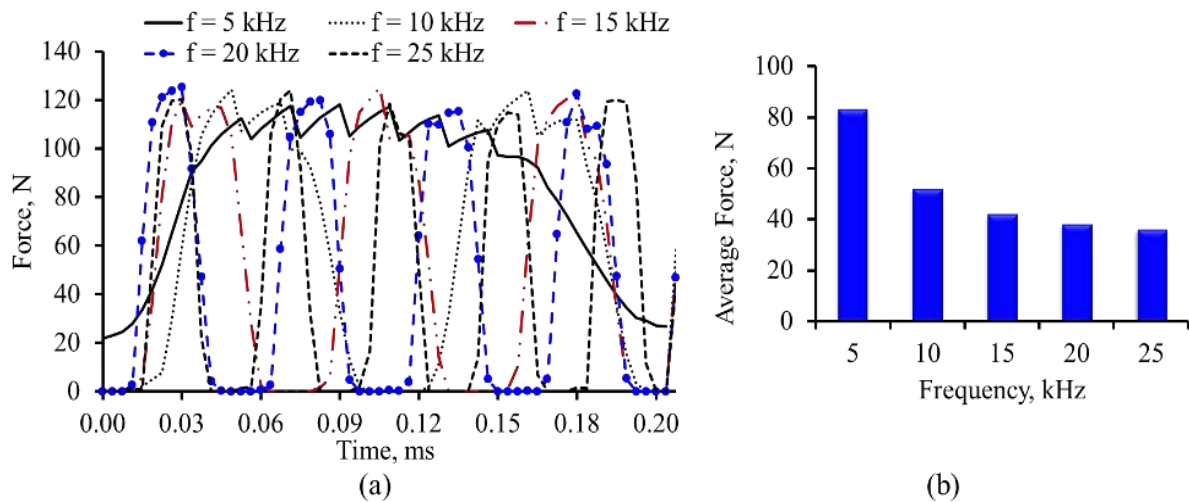


Figure 4: (a) Tangential cutting forces in UAT of Ti alloy; (b) Average cutting force (variable frequency; amplitude 8 μm)

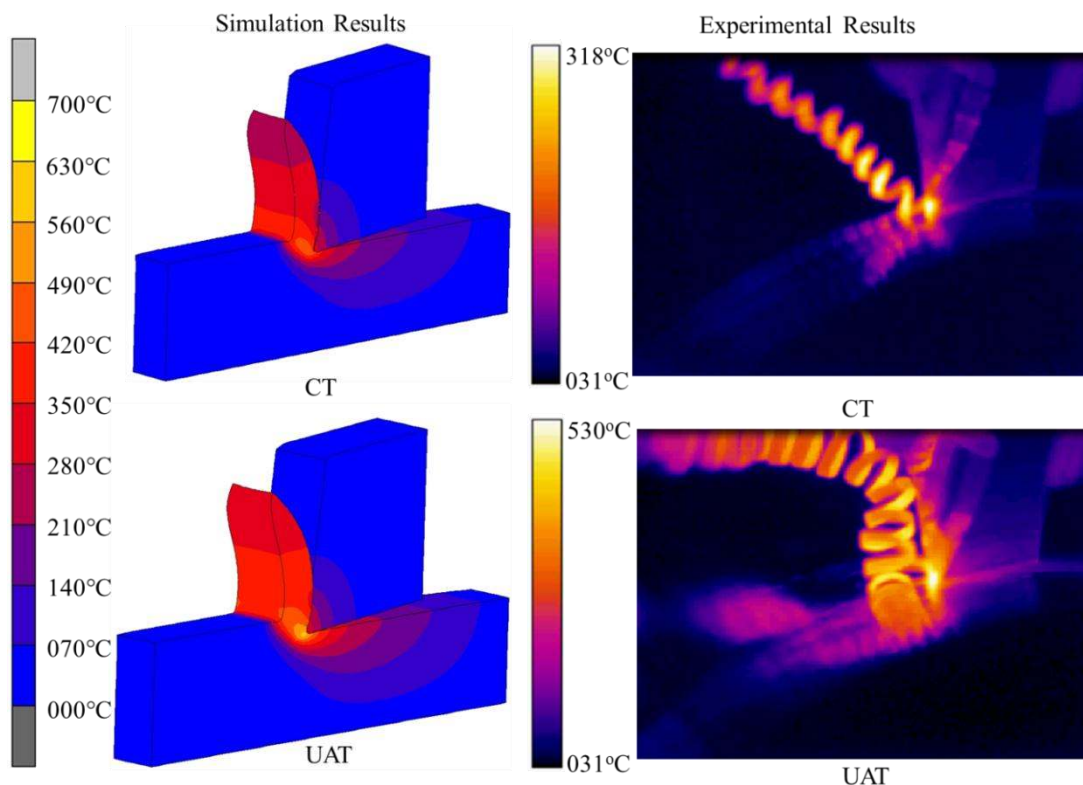


Figure 5: Temperature distribution of the cutting region in CT and UAT (length scale in images of simulation results is much larger than that in thermo-grams)

5. Conclusions

In this study, a 3D thermo-mechanically coupled finite element model for UAT and CT of Ti-6246 was developed. The model was used to undertake a parametric study of the UAT of Ti-6246. The use of this hybrid machining technique resulted in a substantial reduction in the cutting forces in the processing of Ti-alloy. The developed model was validated by experimental results that demonstrated a good agreement.

In future, the current model will be extended to 3D modelling of oblique machining in order to perform a parametric study of UAT using actual tool geometry and to suggest optimize cutting conditions for various type of materials.

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