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Numerical Investigation of Hot Ultrasonic Assisted Turning of Titanium Alloy

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Abstract

Titanium alloys exhibit superior properties such as high strength-to-weight ratio and corrosion resistance but these alloys possess poor machinability. To overcome this disadvantage, new machining methods (Ultrasonic Assisted Machining, Hot Machining etc.) are developed. Hot Ultrasonic Assisted Turning (HUAT) is a new machining method which changes the cutting system between tool and workpiece therefore reduced cutting forces and better surface finish for workpiece are obtained. In this study, 2D finite element (FE) analysis was carried out to investigate the effects of HUAT for titanium alloys. It was confirmed that HUAT technique reduces cutting forces and effective stress significantly but cutting temperature increases compared to conventional turning.

Key words

Finite element modelling; hot ultrasonic assisted machining; titanium alloys; ultrasonic assisted machining; hot machining

1. INTRODUCTION

In recent years, titanium alloys have wide range of applications in automotive, aerospace and biomedical sectors. The reason is that these alloys are light in weight and they have high strength, fatigue and corrosion resistance. However, machining of these materials is very difficult due to their low thermal conductivity. Therefore, conventional machining methods cause low dimensional accuracy and undesired surface roughness. In addition, these alloys can react with cutting tools [1].

Machining of workpiece with the aid of a heat source is called hot machining. External heat sources such as gas torch, furnace preheating, induction heating, electric current heating, plasma and laser heating are most commonly used methods. In early studies of hot machining, ceramic materials are preheated between room temperature and 1400°C. Also, steel products and titanium alloys are preheated from room temperature to 600°C, and Inconel products are preheated from room temperature to 550°C. The results show that preheating of workpiece has a positive impact on tool life, surface roughness, cutting force and machining cost [2-6].

Ultrasonic assisted turning (UAT) is a non-conventional machining technique by applying vibrations to cutting tool at high frequency (20 kHz) and low amplitude (15-20 microns). Using this machining method, cutting forces and surface roughness are reduced. Also, tool wear is reduced and dimensional accuracy is improved. UAT is effective at low cutting speeds, when cutting speed increases, the process outputs (surface roughness, tool wear, cutting force etc.) approaches the outputs of conventional turning operations [7-9].

Hot ultrasonic assisted turning (HUAT) is a new hybrid machining method which is developed in recent years. The method consists of a combination of hot turning (HT) and UAT. In this method, the disadvantage of UAT at high cutting speeds can be eliminated. An early study showed that surface roughness and cutting force are decreased by using HUAT [10].

In this study, HUAT and HT methods are investigated for Ti6Al4V. Both methods are compared with conventional turning (CT) and UAT. In the second part of the study, finite element simulation of HT and HUAT is given. The third section shows the results of finite element simulations. In the last section, conclusions and recommendations are given.

2. FE SIMULATION OF HT AND HUAT

Simulations were performed by using DEFORM 2D software. The number of elements used in the simulations was about 3000 for the cutting tool and 5000 for the workpiece. Because of the remeshing, the number of elements was increased to 6000 for workpiece. A previous study was used to compare the results with UAT and CT [11]. Details of the modeling was given in previous study [11]. Ti6Al4V was used as workpiece material. Dimensions of the workpiece were 3 mm in length and 1 mm in width. Plain strain conditions were applied. FE simulations were performed for four different cutting speeds (10, 20, 30 and 40 m/min) and three different cutting temperatures (20°C, 250°C and 500°C). Ultrasonic vibration was also applied with 20 kHz frequency and 20 µm amplitude. The vibration was applied in the direction of cutting speed. Depth of cut was 0.1 mm and simulations were performed in dry cutting conditions. Table 1 represents the machining conditions of the FE simulations. Fig. 1 shows a screenshot in FE simulation.

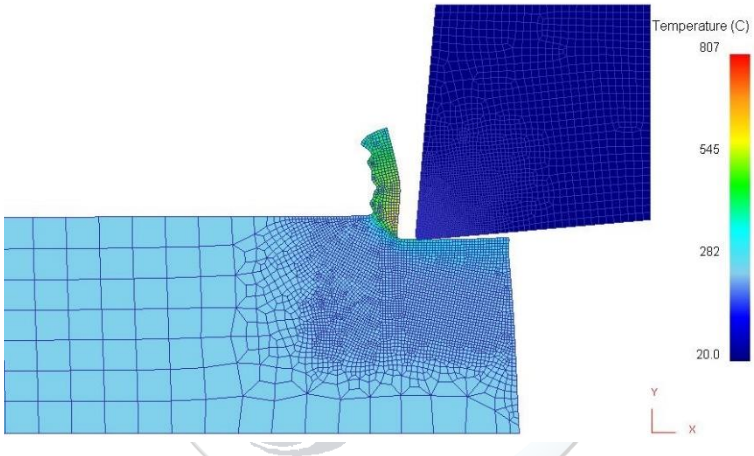

Fig. 1. Screenshot of FE simulation of HUAT

Cutting tool (DNMG 150608 KC 9225) was assumed to be rigid in the simulations. Material of the cutting tool was chosen as non-coated tungsten carbide (WC) and the only thermal calculation for the tool was activated.

Table 1. Machining conditions

Machining Condition	Temperature (°C)	Ultrasonic vibration
CT [11]	20	-
UAT [11]	20	+
HT	250	-
HT	500	-
HUAT	250	+
HUAT	500	+

Johnson-Cook (JC) material model was used in the simulations. The equations of stress and temperature for JC model are given in Eq.1-2. Material parameters used in the simulations for Ti6Al4V alloy are given in Table 2. Values of the parameters were taken from the study performed by Lee [12].

$$\sigma = \left(A + B\varepsilon^{n}\right)\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{0}}\right)\right)\left(1 - T^{*}\right)^{m} \quad (1)$$

$$T^{*} = \frac{\left(T - T_{room}\right)}{\left(T_{melt} - T_{room}\right)} \quad (2)$$

$\dot{\varepsilon}_0$: reference plastic strain rate
ε: plastic strain rate
n : strain rate sensitivity of the material
T_{room}: room temperature
T_{melt}: melting temperature of the material
A, B, C, m : material constants

Table 2. Constants of JC Model suggested for Ti-6Al-4V alloy [12]

A	B	C	n	m	$\dot{\varepsilon}_0$
724.7	683.1	0035	0.47	1	2000 s^{-1}

Fracture criterion has considerable effect on the chip separation therefore Cockcroft & Latham fracture criterion was chosen for the simulations. Similar to materials toughness, fracture limit changes with the temperature. At higher temperatures, continuous chip formation is observed.

3. RESULTS AND DISCUSSION

3.1. Cutting Force Prediction

Improving cutting performance has many aspects. One of the most common approaches is to observe cutting forces. Cutting force results for different machining conditions are presented in Fig.2. The results of the numerical simulation indicate that heating workpiece and applying ultrasonic vibration decrease average cutting force. Simulation results of 30 m/min cutting speed show that at 250°C, cutting force reduction is about 10% and at 500°C, it is nearly 15% compared to CT. One of the most significant advantages of UAT method is the effect of the average cutting forces. At the same conditions, effect of UAT at room temperatures reduces average cutting forces about 35% compared to CT. HUAT at 250°C and 500°C lowers cutting forces about 42% and 57%, respectively compared to CT. HUAT decreases average cutting forces and this hybrid approach is much more efficient compared to the other techniques. According to the numerical results, the lowest cutting force is obtained in HUAT at 500°C. HUAT at 250°C produces promising results therefore heating of workpiece may not be necessary and probably not cost effective at higher temperatures (500°C).

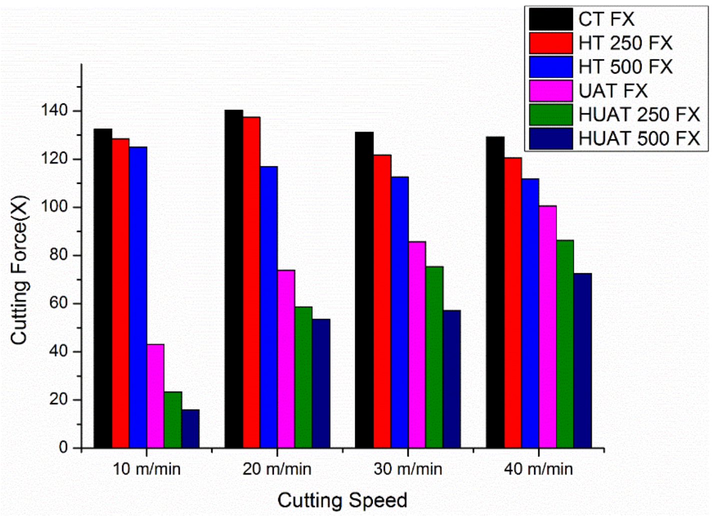

Fig. 2. Average load data for various cutting speeds

3.2. Cutting Temperature

Numerical results show that maximum cutting temperature in HUAT process is slightly higher compared to HT. Fig.3 shows the results of thermal analyses for different cutting conditions.

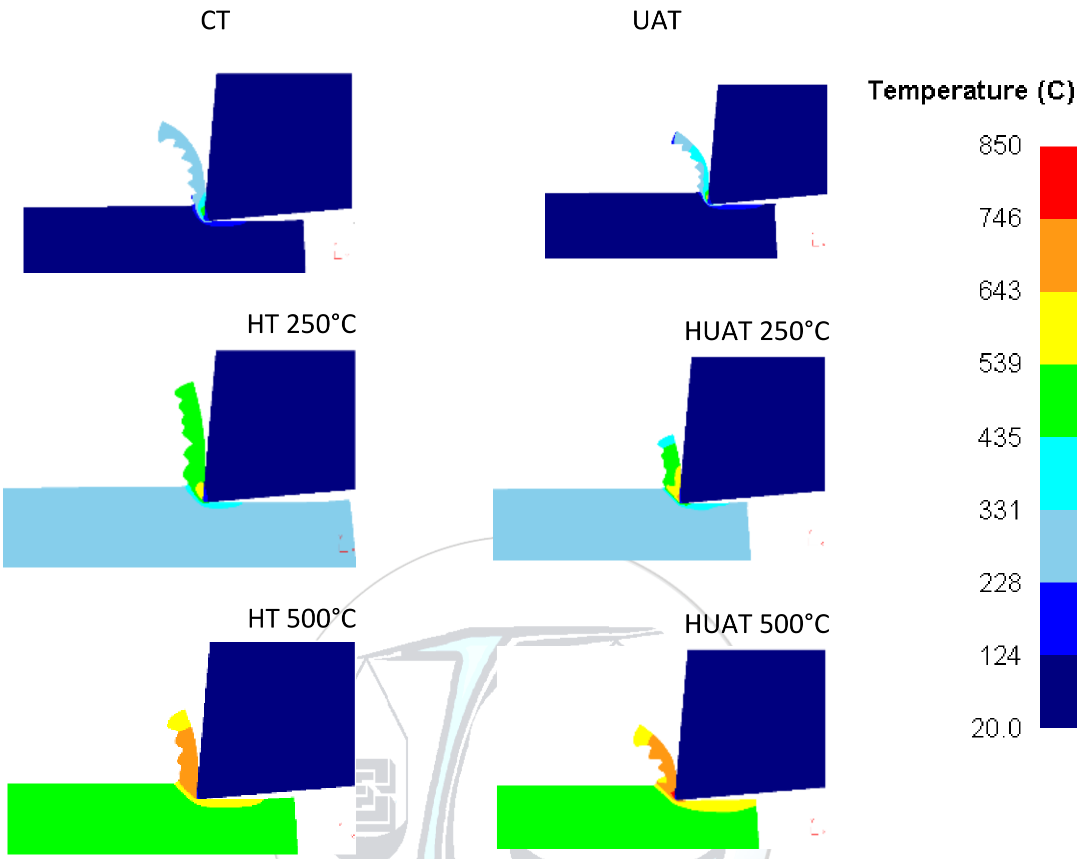

Fig. 3. Temperature distributions in the cutting zone (Cutting speed: 30 m/min)

In HT at 500°C, maximum cutting temperature is nearly 700°C, whereas it is about 800°C in HUAT at 500°C. Applying additional heat increases cutting zone temperature. In HT at 250°C, maximum cutting temperature is nearly 600°C, whereas in HUAT at 500°C, it is about 700°C. Maximum temperatures in the simulations of CT and UAT are about 513°C and 670°C, respectively. In UAT, the maximum cutting temperature increases compared to CT.

3.3. Effective Stresses in the Process Zone

The calculated distributions of effective stresses in the cutting regions of the Ti6Al4V are shown in Fig.4. These stresses are taken at UAT penetration stage because in UAT, stress distribution is changed during each vibration cycle. Maximum effective stress decreases by the increase in temperature as expected. The average levels of the effective stress in the cutting region in HUAT and HT are lower than UAT and CT. Maximum effective stresses in the simulations of CT, HT at 250°C, HT at 500°C are 1300 MPa, 985 MPa, 800 MPa, respectively, whereas in UAT, UAT at 250°C, HUAT at 500°C are 1260 MPa, 995 MPa, 795 MPa, respectively. There are similar findings from previous studies [10].

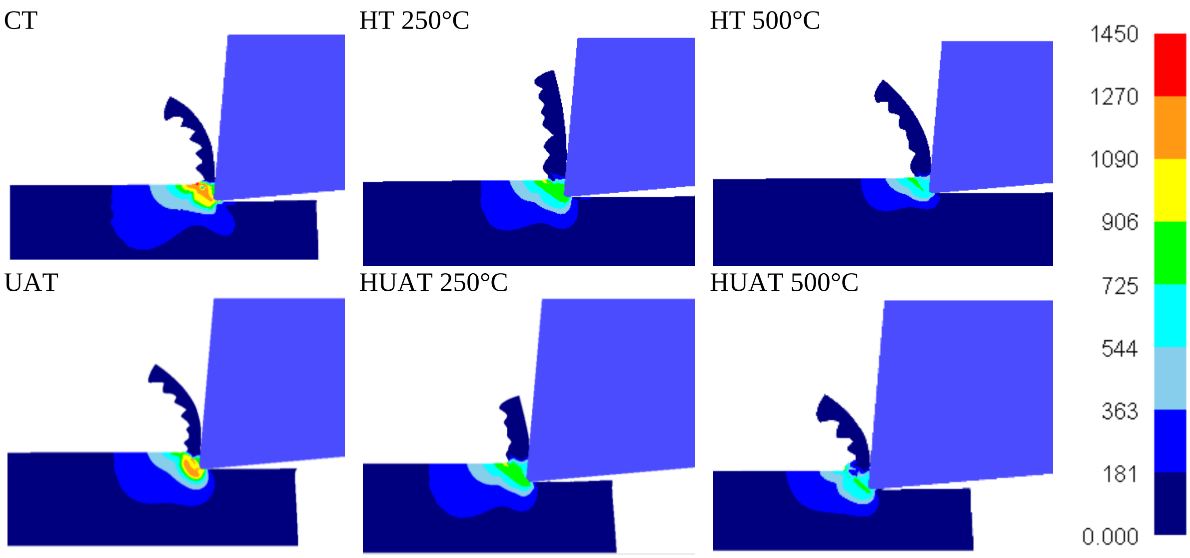

Fig. 4. Effective stresses (MPa) (Cutting speed: 30 m/min)

4. CONCLUSION

In this study, HT and HUAT processes were modeled by FE. The results of simulations demonstrate that HUAT technique reduces average cutting forces significantly but maximum cutting temperature increases compared to the other techniques. Increasing workpiece temperature lowers its yield strength and decreases cutting forces. Reduced cutting forces have many advantages on machining operations. However, lower tool life is obtained because of high cutting temperature. Heat treatments might be applied for cutting tools to avoid increased tool wear. In UAT, reduction of cutting forces is obtained by reducing the tool-workpiece contact area. Furthermore, in HT, thermal softening of workpiece results in reduction in the cutting forces. The average levels of the effective stress in the cutting region in HUAT were lower than UAT and CT. HUAT is much more effective than CT, UAT and HT. Integrating ultrasonic vibrations and heat supply improves machinability of Ti6Al4V. Developed numerical model is useful to understand the effects of process parameters.

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