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TECHNICAL PAPER

Numerical investigation of hot ultrasonic assisted turning of aviation alloys

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Abstract
Aviation 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 hybrid 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 is carried out to investigate the effects of these machining methods on titanium and Hastelloy-X alloys in terms of cutting forces, cutting tool temperatures and effective stresses. DEFORM-2D software is used during analyses. In addition, an experimental study is conducted to verify numerical results. During verification, cutting tool temperature is taken into consideration. It is confirmed that HUAT technique reduces cutting forces and effective stress significantly but cutting temperature increases compared to conventional and ultrasonic assisted turning.

Keywords Finite element modeling · Hot ultrasonic assisted machining · Titanium alloys · Ultrasonic assisted machining · Hot machining · Hastelloy-X

1 Introduction

Ultrasonic technology is used in different production technologies such as ultrasonic cleaning, ultrasonic grinding, ultrasonic welding, ultrasonic turning, ultrasonic hole drilling, etc. Ultrasonic assisted turning (UAT) is a machining process developed by incorporating ultrasonic vibrations into traditional machining processes, which is a new non-traditional machining technique. This process contributes to improve many machining outputs such as surface roughness, tool wear, roundness, surface integrity, etc. Ultrasonic assisted turning provides the improvement of machining operations by applying high frequency (20–40 kHz) and low amplitude (10–20 μm) vibration to the cutting tool. Compared to conventional turning (CT), it provides several advantages for machining of hard-to-cut materials (hard metal alloys, brittle plastics, high-strength aircraft alloys, composites, ceramics) This method reduces machining noise, tool wear and improves surface properties [1]. In the literature, there are several studies to machine hard-to-cut materials such as nickel-based alloys to find optimal cutting conditions using conventional or ultrasonic assisted machining [2–4]. Celaya et al. [5] investigated the effect of ultrasonic assisted machining on workpiece surface Different systems were designed to generate vibrations in two different directions (feed direction and cutting direction). The vibration was applied to the tool holder. The designed set-up was adapted to a conventional lathe. The effect of ultrasonic vibrations on the surface roughness according to different cutting parameters (cutting speed, feed and depth of cut values) was investigated. 1045 steel was used during experiments. The vibration amplitude was 8.1–10 microns and the frequency was 20.1 kHz. Surface roughness was decreased by 6% when the vibration was applied in the feed direction, while surface roughness was improved by 40% when it was applied in the cutting direction.

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Heat-assisted machining is an another method to machine hard-to-cut materials using an external heat source. This method allows the material to reduce the hardness by decreasing the bonding energy and yield strength. Heating of workpiece is developed as an alternative method to conventional machining and can be used in the machining of a variety of materials including metals, ceramic alloys, plastics and composites. Heat-assisted machining provides many advantages comparing to conventional machining such as lower tool wear, and cutting forces, etc. Tensile strength and deformation hardening effect decrease with increasing temperature for high-strength materials. These properties make the heat-assistant machining processes attractive for many industries [6].

In recent years, there are several studies investigating hot machining techniques for hard-to-cut materials such as superalloys, titanium alloys and ceramics. These materials which have high mechanical properties and low thermal conductivity, cause excessive cutting forces and cutting temperatures during the machining processes which leads to decrease in tool life. Lacelle et al. [7] carried out heat-assisted milling operation for nickel-based (Inconel 718), cobalt-based (Haynes 25) and titanium-based (Ti6Al4V) alloys that are widely used in aviation. In their study, a plasma source was used as a heat source and the samples were heated from room temperature to 500–1000 °C. Cutting forces and tool wear were reduced and material removal rates were increased using this method for Haynes and Inconel alloys. As a result, this operation was recommended for rough milling operations. However, this method was not recommended for the use of titanium alloys with higher heat input. It was stated that this heat input may lead to metallurgical changes in the material structure. It should also be noted that it may be possible to use titanium alloys with lower heat input. In their other work, these authors modeled the heat-assisted machining technique for the alloys of Haynes 25 and Inconel 718 by using finite element method [8]. The developed model results were confirmed by the experimental study. 30% reduction in cutting forces was obtained after experimental and numerical study.

Hybrid machining methods are often preferred for many processes to use the advantage of each machining methods. One of the most important hybrid machining methods that have been emerged in recent years for hard-to-cut materials is the hot ultrasonic assisted machining (HUAT) [9]. This method combines the advantages of vibration-assisted machining and heat-assisted machining. In this method, the cutting zone is heated with an external heat source and machining is performed by applying vibration.

In this work, hot ultrasonic assisted turning operations were numerically modeled for Ti6Al4V and Hastelloy-X materials. Three different machining methods (CT, UAT, HUAT) are compared between themselves in terms of cutting forces, cutting temperatures and effective stresses. The verification of the numerical model is performed by comparing experimental cutting tool temperature. To the best of our knowledge, there are limited studies for HUAT modeling of Ti6Al4V and Hastelloy-X. According to the literature survey, the machining of Hastelloy is not sufficiently investigated in terms of CT, UAT and HUAT in numerical studies. According to the results, numerical results exhibit consistency with the experimental outputs. Therefore, the numerical models can be used to investigate the turning operation of Hastelloy-X and Ti6Al4V.

2 Machining methods

2.1 Ultrasonic assisted machining

In this method, the contact with the workpiece is interrupted by the vibration applied in the cutting or feed direction in specific limits. With this interval, cutting forces are reduced and tool life is increased. It is also possible to obtain more stable chip formation. As a result of all these factors, improvement of many properties such as surface roughness, roundness, integrity were reported in the past studies [4, 10–15].

First studies on the use of vibrations in machining applications began in the late 1950s [16]. These studies have used a one-dimensional (1D) oscillation motion. Two-dimensional (2D) vibration applications have been developed in the 1990s, especially for the machining of ceramics and glass [16]. According to the studies performed, 2D vibration applications have superior machining properties compared to 1D vibration applications. Especially in optical applications, it has been used to produce complex shapes [17, 18]. Studies on 2D vibration are focused on micro-machining of materials such as glass and ceramics, while studies on 1D vibration applications are used for aerospace materials that a machine using conventional methods [10, 11, 13, 19, 20].

In ultrasonic assisted machining applications, the cutting edge moves harmonically in the cutting direction. This process basically has four stages. These stages are approach, contact, immersion, and back off (Fig. 1). Using high-vibration frequency values, many cycles occur in a shorter period of time less than a millisecond. The equations of motion for of one-dimensional vibration are given in Eqs. 1–3. In these equations, f is the frequency of vibration, A is the amplitude of vibration, t is the time and ω is the angular frequency. The position and speed of cutting tool is expressed as follows:

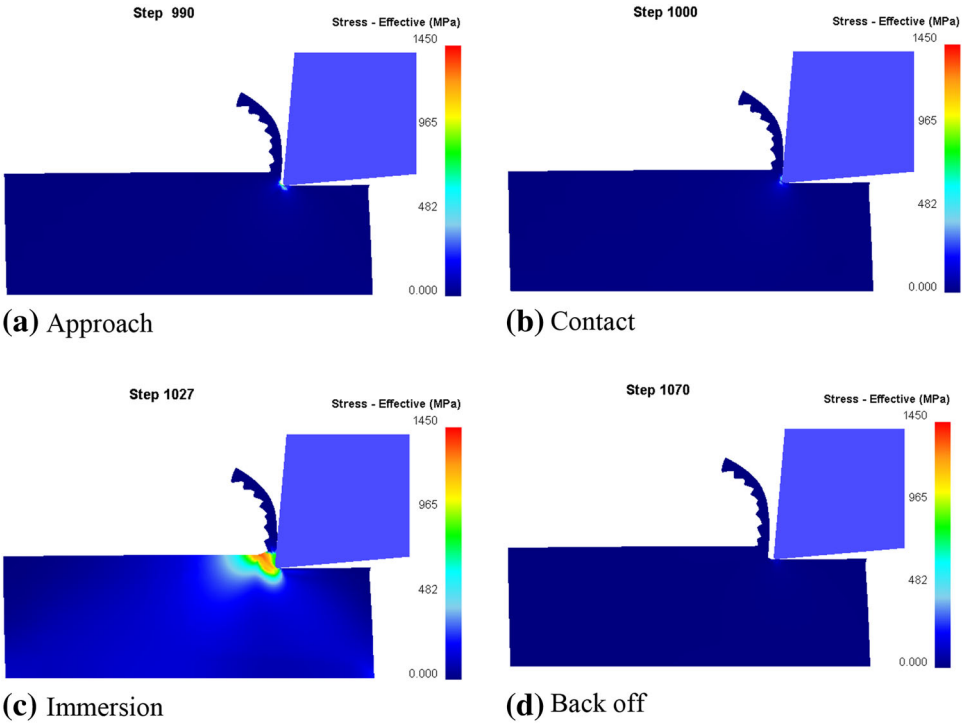


Fig. 1 The stages of ultrasonic assisted machining process

$$x(t) = A.\sin(\omega t) + Vt, \tag{1}$$

$$x'(t) = \omega A\cos(\omega t) + V, \tag{2}$$

$$\omega = 2\pi f. \tag{3}$$

According to this definition, it can be said that the velocity of the tool according to the workpiece follows a sinusoidal wave. The back off stage of cutting tool is observed where the x' is negative. Therefore, the case where the first term in Eq. 2 is equal to V expresses the maximum speed at which contact can be interrupted. When the $\cos(\omega t)$ expression is equal to -1, the magnitude of ωA equals to V, and it gives the critical speed value for intermittent cutting (Eq. 4).

$$V_c = 2\pi Af. \tag{4}$$

2.2 Hot machining

Hot machining is a process that aims to improve cutting process by softening the materials which are difficult to machine. Several studies were carried out for this purpose at the end of 90s. Electrical current is passed through the contact point between the cutting tool and the workpiece and the workpiece is heated and softened using resistance effect [21]. More comprehensive studies in this area came to light in the 1950 and outputs such as reduced cutting forces and increased tool life were obtained [22]. Nowadays, hot machining is an important alternative for hard-to-cut materials such as superalloys, titanium alloys and ceramics. These materials, which have high mechanical properties and low thermal conductivity, cause excessive cutting forces and cutting temperatures during the machining process. These conditions obviously reduce the tool life. Hot machining method eliminates many of these disadvantages.

Hot machining uses external heat systems to heat the workpiece during or before machining processes. The main methods used for this purpose are plasma heating, laser heating, induction heating, flame heating, furnace heating, electron beam heating, etc. Each method has its own advantages and disadvantages [23].

3 Numerical study

In this study, cutting tool is used in orthogonal cutting conditions. To model orthogonal cutting conditions, 2D finite element model is developed using DEFORM-2D software. In this context, Langrange finite element solver is used by continuous and adaptive meshing method. Dry cutting condition is used. 2D simulation studies in machining are chosen due to the simplicity and the shorter solution time. Two different materials Ti6Al4V and Hastelloy-X are used as workpieces. Workpieces are modeled as plastic. In the simulations, ultrasonic vibration is applied at 20 kHz and 20 microns in the cutting direction of the cutting tool. The feed rate is taken as 0.1 mm/rev. Cutting speed is selected as 40 m/min. These parameters

are determined according to different literature studies [4, 24]. Generally, cutting speed is selected under 50 m/min and feed rate is chosen under 0.2 mm/rev. to observe the advantage of the ultrasonic assisted machining method. The optimum number of elements is determined as 3000 elements for workpiece and 2500 elements for the tungsten carbide tool in simulation of Ti6Al4V machining, whereas 2500 elements for Hastelloy-X and 1500 elements for the tungsten carbide tool for the simulation of Hastelloy-X machining after different trials. With the help of remeshing, the number of mesh is increased in the cutting region at the time of cutting. In the simulations, X is the cutting direction and Y is the feed direction (Fig. 2). The lower part of the workpiece is fixed in the Y-axis direction. The cutting tool can move in X- and Y-directions.

For conventional and ultrasonic assisted turning, the initial temperature of the workpiece is set to 20 °C and for hot ultrasonic assisted turning, the initial temperature is set to 150 °C for the workpiece. The Johnson–Cook material model is used to model workpieces. In high strain events, this model produces accurate results. In addition, this model shows the precision of the strain rate at the material. Equations for this model are given in Eqs. 5–6. Table 1 shows the coefficients of the models used in simulation.

$$\sigma = (A + B\varepsilon^{n})\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right)(1 - T^{*})^{m}, \tag{5}$$

$$T^{*} = \frac{(T - T_{\text{room}})}{(T_{\text{melt}} - T_{\text{room}})}, \tag{6}$$

Table 1 Johnson Cook coefficients for materials used in simulations [25, 26]

Materials	A (MPa)	B (MPa)	C	n	m	$\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}$
Hastelloy-X	380	1200	0.012	0.55	2.5	0.001
Ti6Al4V	724.7	683.1	0.035	0.47	1	2000

$\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}$: strain rate/reference strain rate, n: Strain rate sensitivity for the material, T_{room}: Room temperature. T_{melt}: Melting temperature of workpiece, A, B. C, m: Material constants.

Johnson–Cook material model coefficients are determined based on experimental work and the curve fitting of experimental results. In the experimental work, material test (Split Hopkinson test) is applied and the mechanical characteristics of the material are determined according to different strain rates and temperatures. The coefficients in Table 1 weredetermined by previous studies.

The cutting tool material is WC + TiAlN coated with a rake angle of 0° and a clearance angle of 7°. The tool's hone radius is 0.02 mm. During machining, the serration of chips affects many parameters such as chip shape, cutting temperature and cutting forces. For this reason, it is necessary to take this phenomenon into account in machining simulations. The Cockcroft and Latham fracture criterion is used in this study. Therefore, the morphology of chip formation could be simulated. This coefficient is chosen as 100 for Ti6Al4V alloy. This coefficient and criterion have

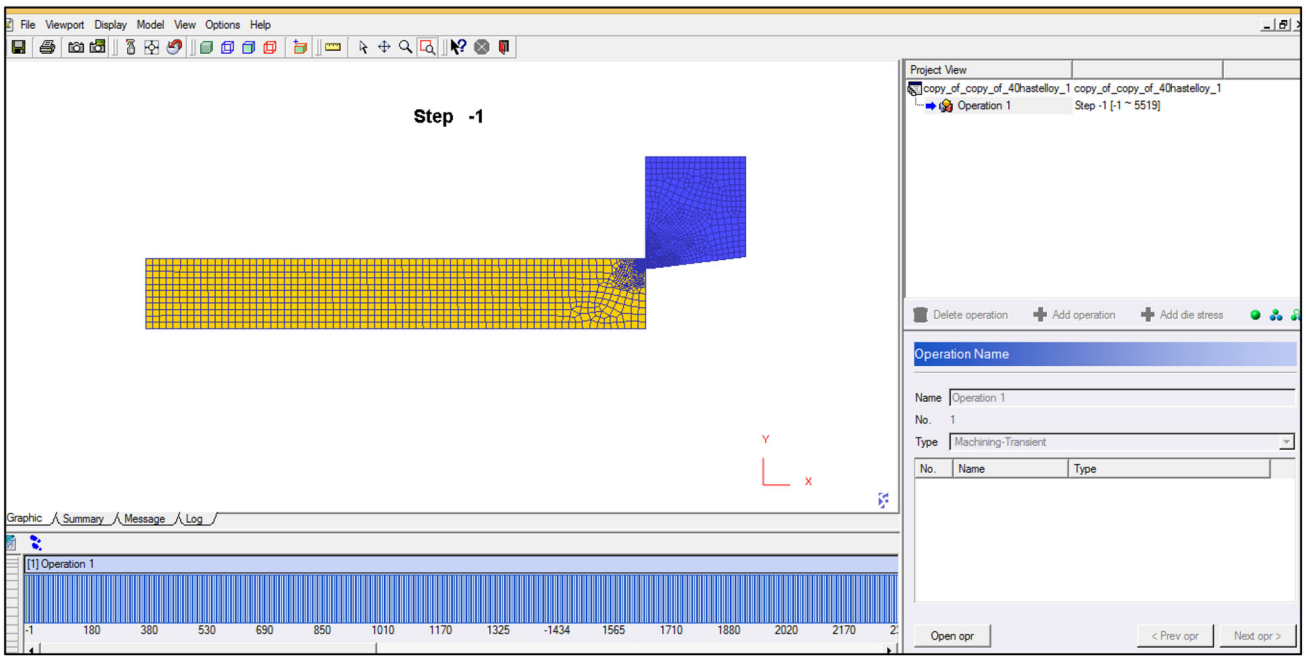


Fig. 2 Simulation screenshot from Deform 2D software

been determined in the previous work done in the literature [27]. For the Hastelloy-X material, similar studies were performed in the literature [28].

Friction model and coefficients are determined using different studies in the literature. In the simulation of machining of Ti6Al4V, the friction zone is divided into three regions (Fig. 3). The part of the tool radius is taken as shear friction and the value is 1.0, from the point where the tool tip radius ends, the uncut chip thickness is taken as the shear friction at the upper region and the value is 0.7. The third part to the point where the contact of the chip is finished is taken as coulomb friction and the value is 0.5 to represent the rubbing effect. A previous study and different trials are used to determine these regions and coefficients [29, 30].

The friction zones are determined for the modeling of Hastelloy-X. The friction zone is divided into two sections for Hastelloy-X machining. The part of the insert radius is taken as shear friction and the value is 0.9. The second zone is defined on the top of this region to the portion where the chip contact is finished. This zone is determined as coulomb friction and the value is taken as 0.7. A similar approach has been used for the modeling of a nickel based material in the literature [30]. Material properties for Hastelloy and Ti6Al4V are using literature studies and given in Table 2 [29, 31, 32].

4 Numerical results and discussions

In this section, numerical findings are discussed in terms of average cutting forces, maximum temperatures on cutting tool and effective stress values.

4.1 Average cutting forces

Calculated average cutting forces for Hastelloy-X and Ti6Al4V are given in Figs. 4, 5, and 6, respectively. In ultrasonic assisted turning, cutting forces are decreased by more than 50% compared to conventional turning for Hastelloy-X, while these forces are decreased nearly 70% for Ti6Al4V alloy. Hot ultrasonic assisted turning shows a decrease which is about 5% compared to ultrasonic assisted turning for both materials.

In the literature, it has been reported that the cutting forces are significantly reduced in comparison with the studies performed on vibration compared to the conventional operations [9, 20, 24, 33].

The reduction of the average cutting forces with the effect of vibration and intermittent cutting is one of the most important advantages of the UAT process. The magnitude of cutting forces observed during the cutting operation for one-dimensional vibration is nearly same as the cutting forces obtained by conventional turning, but the average force is considerably reduced due to the fact that the cutting force is near zero when it is in the interval stage.

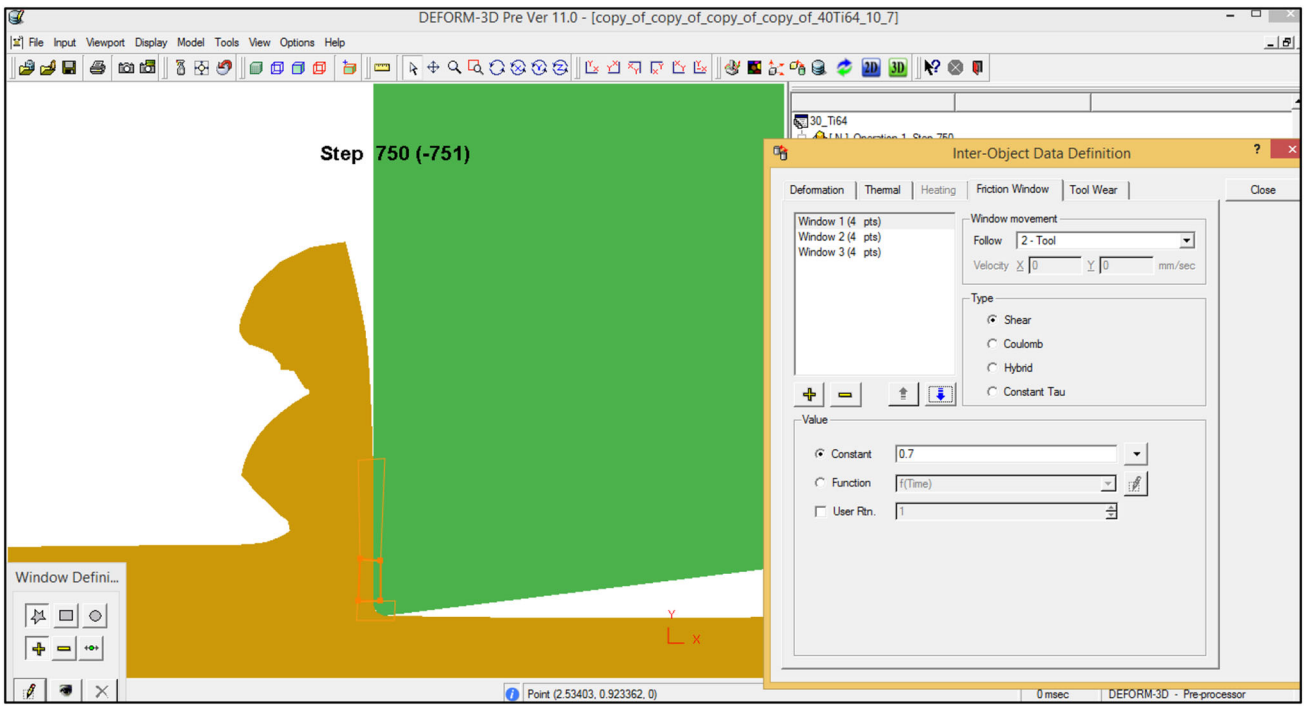


Fig. 3 Friction zones of Ti6Al4V during machining simulation

Table 2 Mechanical and thermal properties of materials used in simulations [29, 31, 32]

Material properties	Ti6Al4V	Hastelloy-X
Modulus of elasticity (MPa)	0.7412 T + 113,375	209199.4–62.221 T
Thermal expansion ($mm.mm^{-1}$ $°C^{-1}$)	$3 \times 10^{-9}T + 7 \times 10^{-6}$	$1.3 \times 10^{-5} + 2.76e \times 10^{-9}T$
Thermal conductivity ($W.m^{-1}$ $°C^{-1}$)	$7.039\ e^{0.0011T}$	$10.5e^{1.115e-3T}$
Emissivity coefficient	0.7	0.85
Poisson's ratio	0.31	0.32

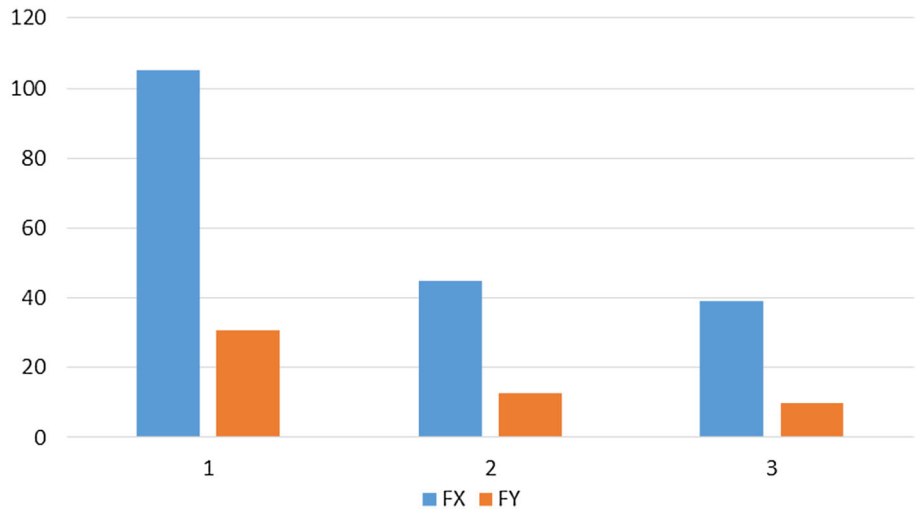


Fig. 4 Average cutting forces (*N*) according to different turning methods of Hastelloy-X (1-CT/2-UAT/3-HUAT)

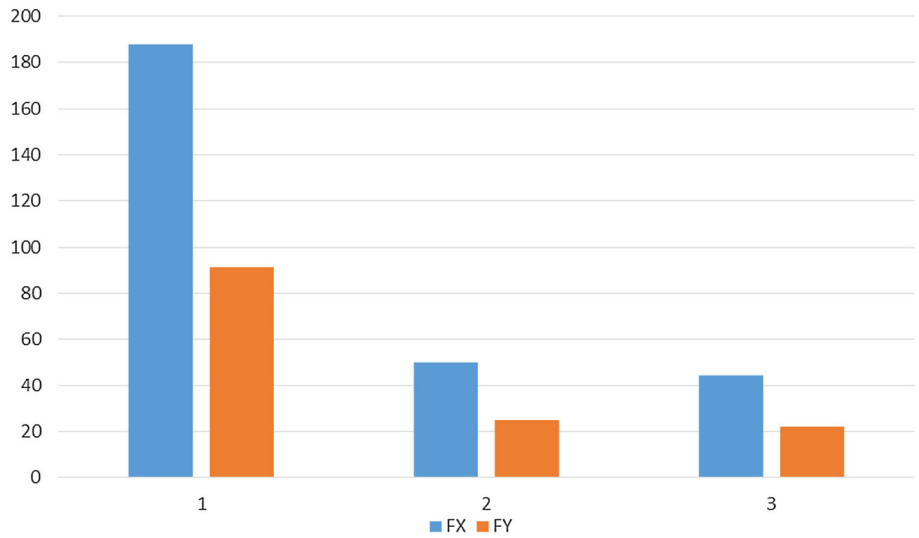


Fig. 5 Average cutting forces (*N*) for different turning methods of Ti6Al4V (1-CT/2-UAT/3-HUAT)

Because these changes occur in small intervals, observing this effects experimentally is not possible.

4.2 Effective stress

Effective stress distributions of ultrasonic assisted machining for Ti6Al4V are given in Fig. 7. In conventional turning of Ti6Al4V, the maximum effective stress is nearly 1200 MPa, while in the case of hot ultrasonic assisted turning of Ti6Al4V, it reaches about 900 MPa.

Effective stress distributions of conventional, ultrasonic and hot ultrasonic assisted machining of Hastelloy-X are given in Figs. 8, 9 and 10, respectively. In conventional turning of Hastelloy-X, the maximum effective stress is approximately 1600 MPa, while in the ultrasonic assisted turning, it reduces to 1250 MPa. In hot ultrasonic assisted method, it is nearly 1000 MPa.

It is expected that as cutting forces decrease, maximum effective stress also decreases.

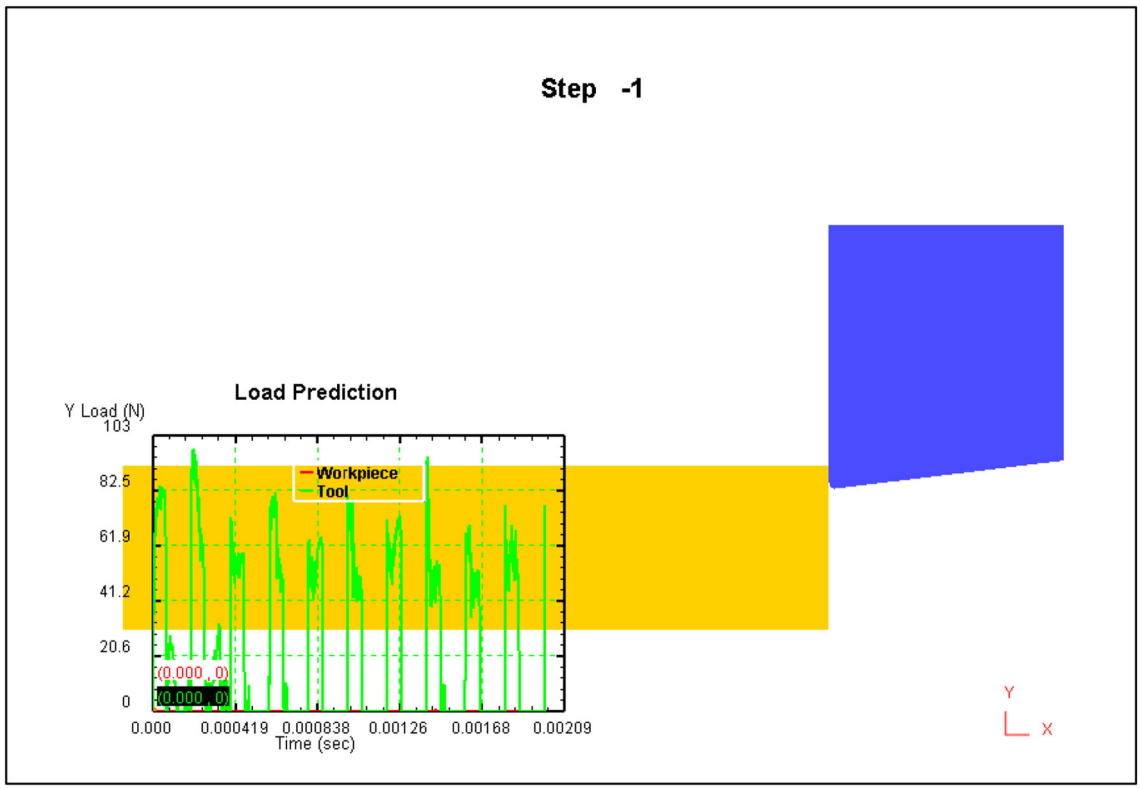


Fig. 6 F_y (N) for hot ultrasonic turning of Ti6Al4V

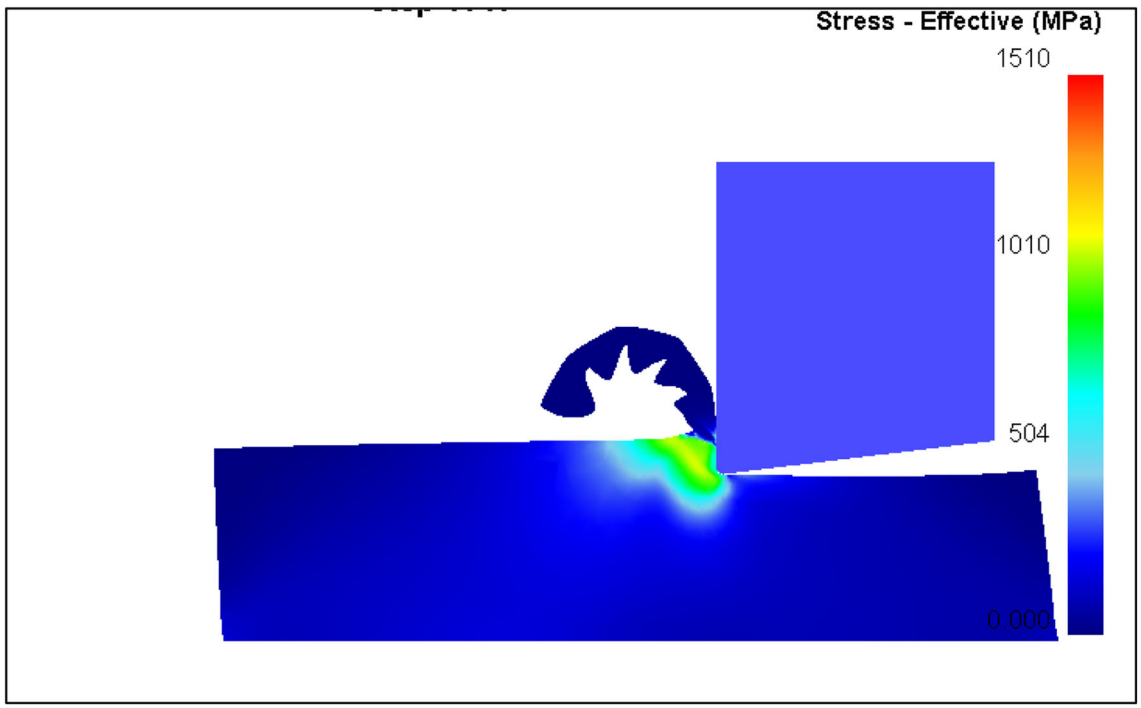


Fig. 7 Effective stress distribution in ultrasonic assisted turning of Ti6Al4V

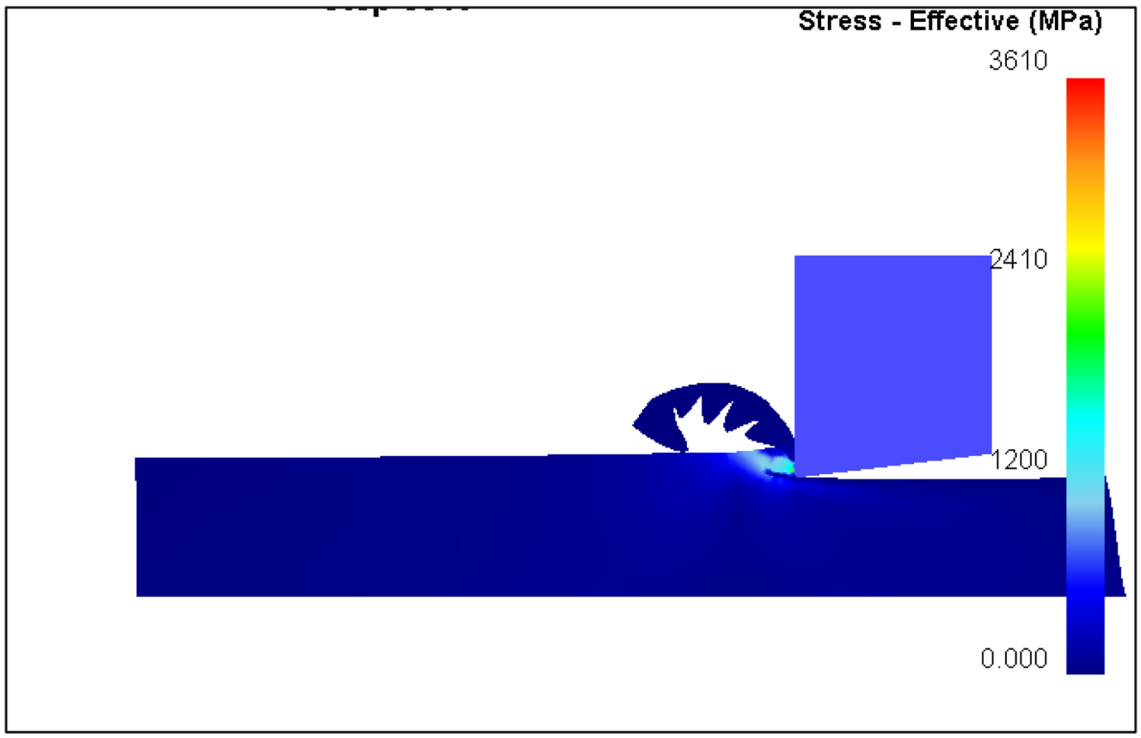


Fig. 8 Effective stress distribution in conventional turning of Hastelloy-X

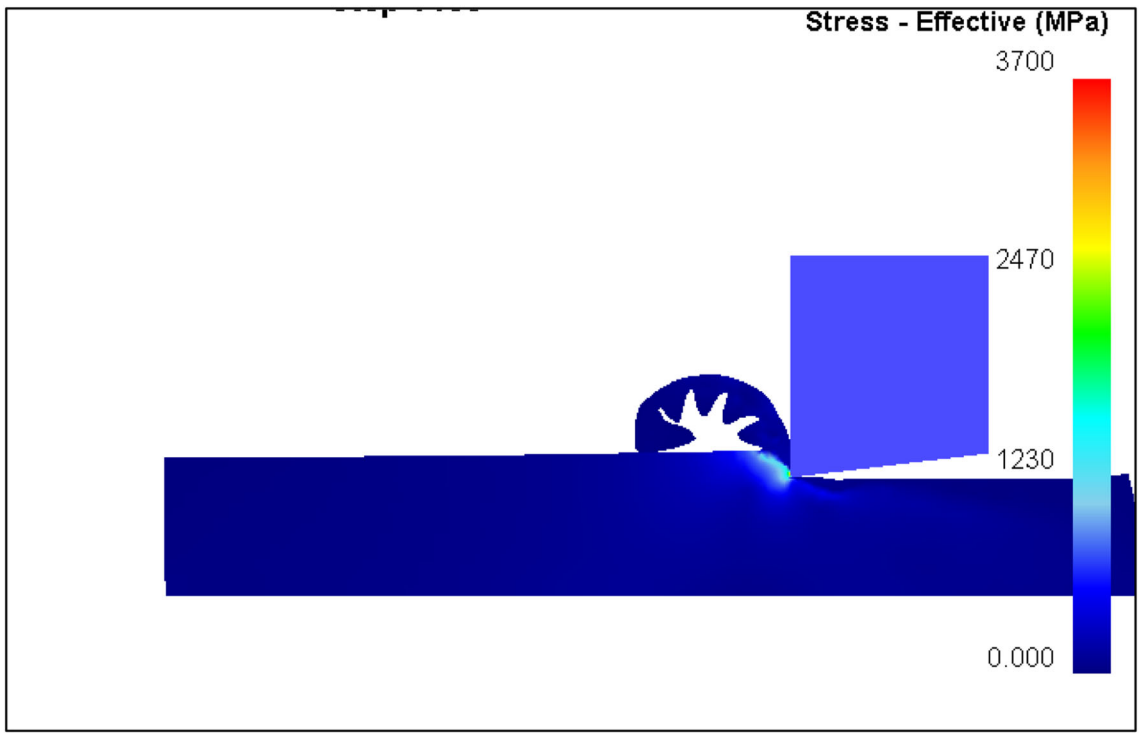


Fig. 9 Effective stress distribution in ultrasonic assisted turning of Hastelloy-X

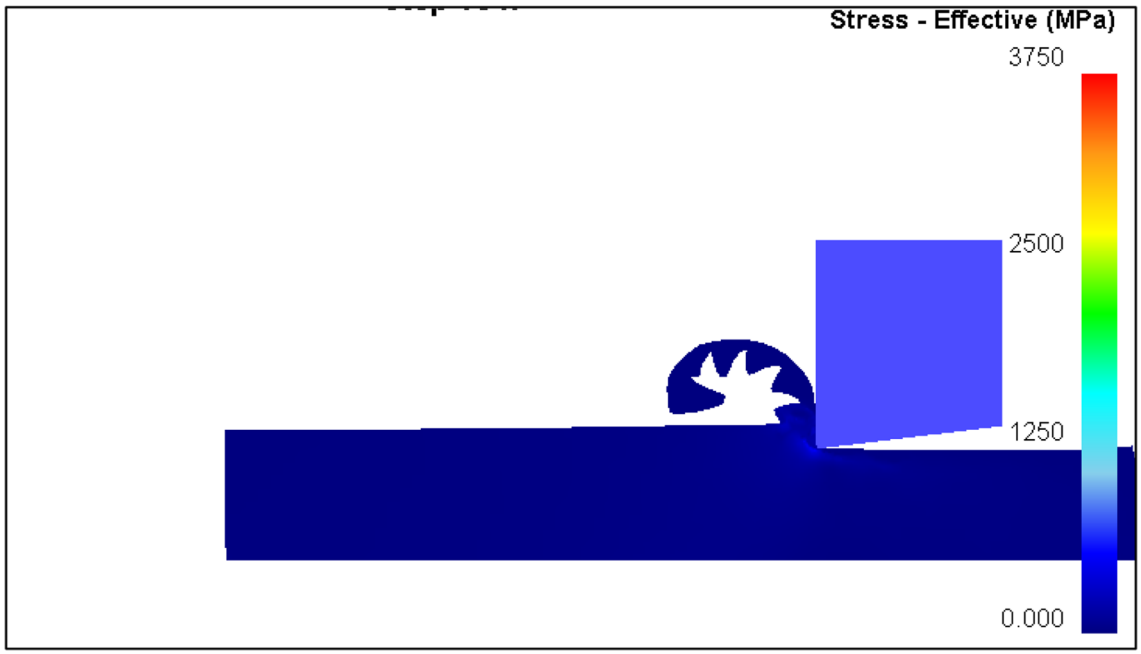


Fig. 10 Effective stress distribution in hot ultrasonic assisted turning of Hastelloy-X

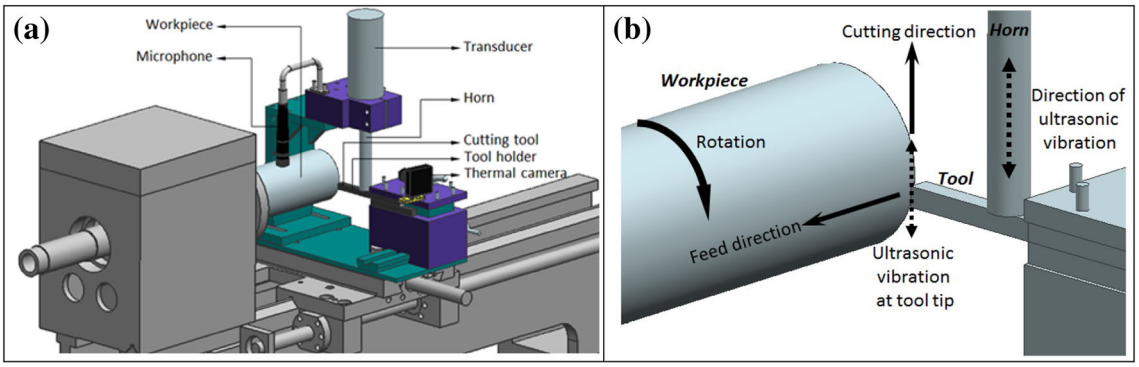


Fig. 11 **a** Experimental setup and **b** detailed view of process

4.3 Maximum temperatures on cutting tool

Experimental tests are performed to verify the numerical models. The experimental setup is shown in Figs. 11, and 12. The vibration frequency is 20 kHz and vibration amplitude is 20 microns. These magnitudes are measured at test setup with oscilloscope and indicator measurement. To amplify vibration, transducer is excited at close ranges to the natural frequency. In the UAT operations, a fixture is utilized to integrate the ultrasonic unit into the system and vibrational motion is excited in the cutting direction.

To observe the cutting tool temperatures, a thermal camera is focused on the cutting area and a thermocouple is also used to measure temperature on the insert. For HUAT operations, the preheating furnace, which is able to reach the maximum temperature of 400 °C, is used.

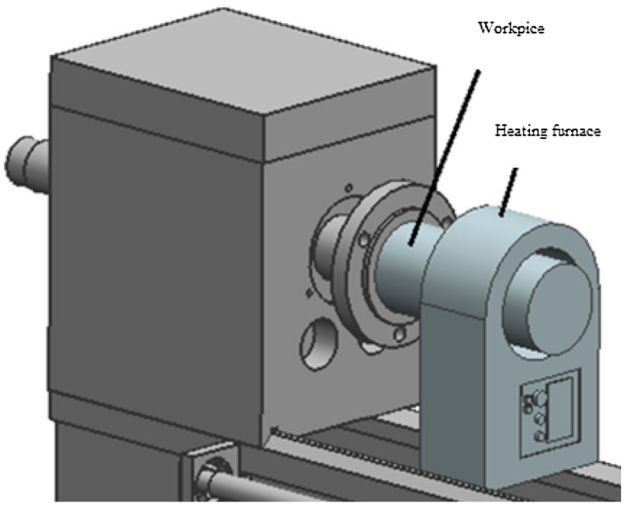


Fig. 12 Heating furnace

Table 3 Maximum temperatures on cutting tool (Hastelloy-X)

Turning operations	Experimental (°C)	Numerical model (°C)
Conventional turning	183.45	167.72
Ultrasonic assisted turning	192.45	184.80
Hot ultrasonic assisted turning	298.80	254.10

Table 4 Maximum temperatures on cutting tool (Ti6Al4V)

Turning operations	Experimental (°C)	Numerical model (°C)
Conventional turning	208.20	167.73
Ultrasonic assisted turning	237.20	241.54
Hot ultrasonic assisted turning	349.25	271.83

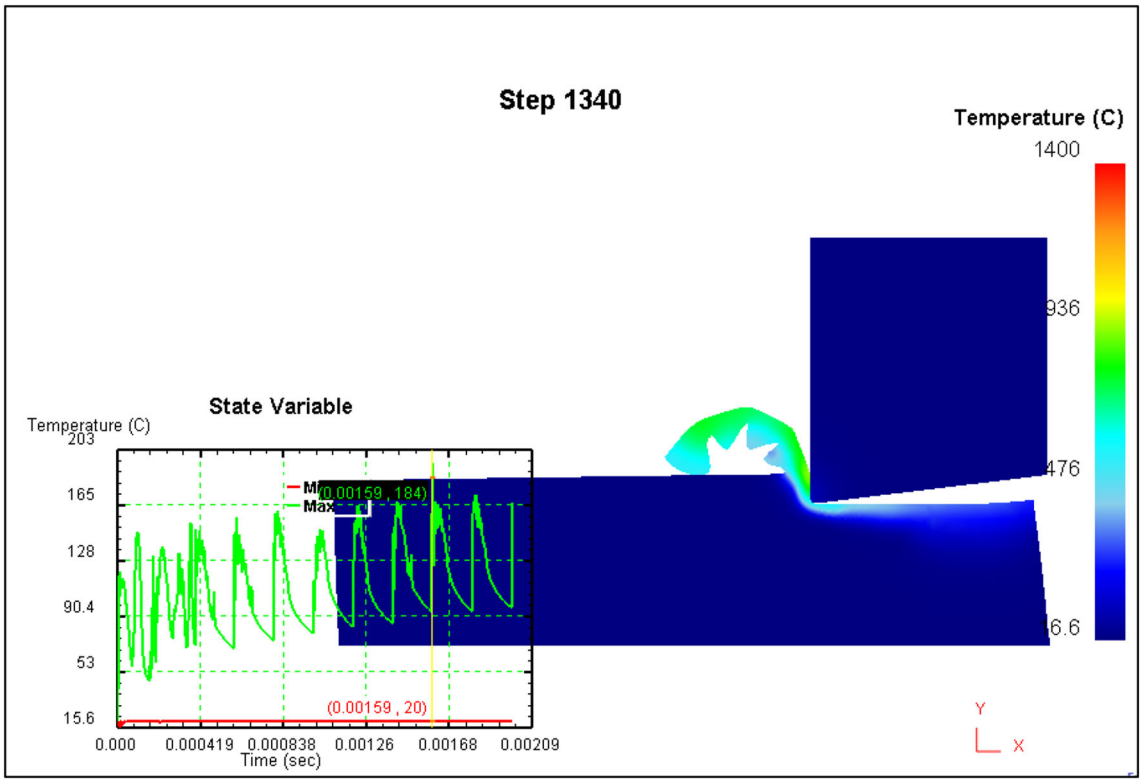


Fig. 13 Temperature distribution during ultrasonic assisted turning of Hastelloy-X

Maximum cutting temperatures at the cutting edge observed during machining of Ti6Al4V and Hastelloy-X are given in Tables 3, and 4, respectively. When the results are examined, it is obtained that developed numerical model simulates conventional and ultrasonic assisted turning operations with maximum 25% error. In this context, it is observed that the numerical model satisfies the experimental results. In Fig. 13, temperature distribution of ultrasonic assisted turning of Hastelloy-X is given.

UAT operation reduces cutting temperatures because tool retraction in each vibrational cycle allows the cutting fluid to reach the cutting zone [34, 35]. For this reason, heat transfer from cutting zone accelerates despite the additional heat input arising from vibrational energy. In this study, dry cutting is applied for the operations and thereby UAT operation exhibits an increase in temperature in comparison to CT operation. On the other hand, high level temperatures are seen in HUAT method due to the external heat source in addition to vibrational energy. Furthermore, cutting temperatures increasewith the increase in cutting speed as stated by Muhammad et al. [35].

5 Conclusion

Ultrasonic assisted machining is a promising technology for machining difficult to cut materials. In this study, machining of Hastelloy-X and Ti6Al4V is modelled and analysed by using finite element method. CT, UAT, HUAT operations are taken into consideration in terms of cutting forces, cutting temperatures and effective stress. The findings are given below:

- In ultrasonic assisted turning, average cutting forces are decreased by more than 50% compared to conventional turning for Hastelloy-X, while these forces are decreased nearly 70% for Ti6Al4V alloy.
- In conventional turning of Hastelloy-X, the maximum effective stress is approximately 1600 MPa, while in the ultrasonic assisted turning, it reduces to 1250 MPa with the effectof ultrasonic vibrations. In hot ultrasonic assisted turning, additional heatingalso lowers the effective stress which is about 1000 MPa.
- In conventional turning of Ti6Al4V, the maximum effective stress is nearly 1200 MPa, while in the case of hot ultrasonic assisted turning of Ti6Al4V, it is approximately 900 MPa.
- Maximum cutting temperature increases in ultrasonic and hot ultrasonic turning because of applied external energy.
- Developed models are verified with the experimental cutting tool temperatures.

The proposed numerical model is useful to understand the effects different turning operations (CT, UAT, HUAT). Different cooling strategies can be applied in future studies. In addition, different hybrid machining methods might be developed. In addition, different parametric studies can be performed in the simulations.

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