Experimental investigations and simulation models validation on the machinability of Ti-6Al-4V during Ultrasonic vibration assisted turning

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Abstract

Titanium alloys have got wide attention due to its huge application in the field of biomedical, aerospace and marine industries. The unique characteristics like high strength to weight ratio, matchless corrosion resistance, and high tensile strength have increased their demand to a great extent. Still, properties like high hardness at elevated temperature, affinity to react with the tool and reduced thermal conductivity make these as hard to cut alloys. Ultrasonic vibration assisted turning (UVAT) is one of the innovative methods to process these alloys compared to the conventional turning (CT). In this process, an ultrasonic frequency of 20 kHz with small amplitude is led to impose on the cutting tool to get an intermittent cutting unlike the conventional machining. The present work consists of two parts. The first part includes understanding of both the processes using finite element models prepared by Deform 3D® v 10.0. The second part investigates the machinability like cutting force and tool tip temperature of Titanium alloy, Ti-6Al-4V during CT and UVAT. The effects of input parameters on the machinability have been investigated. UVAT process is found to be a superior and feasible process over CT by reducing the cutting force and tool temperature. However, the tool temperatures during UVAT process are noticed to surpass the temperatures generated during CT process at higher value of cutting velocity, feed rate and depth of cut that limits to choose proper cutting combinations. Finally, the models are validated comparing with the experimental findings.

Keywords: Conventional turning; Finite element models, Machinability; Ti-6Al-4V; Ultrasonic vibration assisted turning

1. INTRODUCTION

With advancement, industries are demanding novel machining methods to process new alloys which are relatively hard to machine using conventional turning (CT). Ultrasonic vibration assisted turning (UVAT) is one of the novel methods to process these alloys. This method has been rigorously researched and explored by several researchers due to its advantages like reduction in cutting force and surface roughness generating a better surface compared to Conventional turning [1]. These advantages are owing to the imposition of ultrasonic vibration on the cutting tool producing an intermittent motion of the cutting tool. A comparative investigation of the effects of cutting control parameters like cutting velocity, feed rate, amplitude, frequency on cutting force generated during both the processes, was studied by Ahmed et al. [2]. He concluded that the reduction of force during UVAT was due to the increase of amplitude and frequency. Nath et al. [3, 4] studied the UVAT while machining low alloy steel and Inconel 718 and asserted that the reduction in average force was due to the lower tool workpiece contact ratio (TWCR). Dong et al [5] assessed the effect of tool geometry like rake angle, side cutting edge angle and nose radius on the average cutting force and tool wear while processing reinforced aluminum matrix using both UVAT and CT. He noted significant reduction in cutting force on applying ultrasonic vibration whereas the force generation characteristics due to tool geometry were similar to the CT.

Several researchers inspected the machinability of Titanium alloys during UVAT. S. Koshimizu [6] mentioned that the lower cutting velocity played a key role in reducing average force, tool wear and surface roughness. He suggested the cutting velocity should be 30% of the critical velocity or cutting tool tip velocity during machining of Ti-6Al-4V using UVAT. Muhammad et al [7] carried out several experimental and computational studies regarding the machinability improvements during UVAT in terms of reduction in cutting force, surface roughness and tool wear. He explained and investigated the intermittent mechanism of cutting tool during UVAT by building thermo- mechanical finite element models using MSC MARC®. Patil et al. [8] carried out 2D finite element models using Deform 2D understanding the interface temperature, stress and strain generation during turning operations along with experimental and metallurgical investigations while machining Ti-6Al-4V. Khajehzadeh et al. [9] assessed the effects of various input parameters like feed rate, cutting velocity, amplitude and frequency on the tool temperature generation during both CT and UVAT. He concluded that UVAT process was favorable method enhancing the machinability of aerospace aluminum by reducing the tool temperature only during the lower and limited cutting velocity. The present work aims on building thermo- mechanical finite element models for both the machining processes using Deform 3D®. The models have been validated on comparing the simulated results with the measured ones.

2. FINITE ELEMENT MODELLING OF CT AND UVAT

Thermo-mechanical finite element models were built to understand the mechanism and to predict the output responses using commercially available package Deform 3D® v 10.0. The workpiece material is titanium alloy, Ti-6Al-4V and the tool is multi layered coated tungsten carbide insert, SNMG 120408 with grade TN- 4000 supplied by Widia, India. The workpiece was considered as plastic deformable body whereas the tool as rigid due to high hardness. The models were meshed properly with fine mesh element at the contact zone of size 30 µm to

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achieve accuracy in results. The remeshing criteria were adopted for smooth conduct of the simulation. A non-linear Johnson and Cook model [10] given by Eq. (1) was assigned to the workpiece material with the material constants shown in Table 1.

$$\sigma = \left[A + B\varepsilon^{n}\right]\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left[1 - T^{*m}\right] \quad (1)$$

$$T^{*} = \frac{T - T_r}{T_m - T_r}$$

Where, σ, ε, $\dot{\varepsilon}$ are stress, strain and strain rate respectively. T_r and T_m are the room temperature and melting temperature of TI-6Al-4V respectively. A, B, C, n, m are the yield stress coefficient, plastic strain coefficient, strain rate coefficient, hardening coefficient and thermal softening coefficient respectively given in the Table 1. A simple shear friction model (Eq. 2) was incorporated at the friction zone with a friction factor, 0.82 [11].

$$\tau = km \quad (2)$$

Where, τ, k, and m are friction force, equivalent shear stress, and shear friction factor respectively. The kinetic boundary conditions were assigned to the workpiece keeping top surface free with a cutting velocity of 18 m/min. The cutting tool was fixed for CT whereas; the tool was assigned to an oscillating motion with critical velocity for UVAT simulation. The critical velocity, V_t can be found out from the following Eq. (3).

$$V_t = 2 * \prod * f * a \quad (3)$$

Where, V_t, f and a are critical tool tip velocity, frequency and amplitude of the ultrasonic vibration.

Table 1- Material coefficients for JC model [12]

Variable	$\dot{\varepsilon}$	A	B	C	n	m	α
Unit	1/s	MPa	MPa				
Value	2000	724.1	683.1	0.035	0.47	1	0

The thermal boundary conditions were applied to the workpiece and cutting tool for temperature evaluation. The heat loss at the interface zone was characterized with the following Eq. (4) [10].

$$q = h\left(T_W - T_t\right) \quad (4)$$

Where, q is the heat loss in kW/m^2, h is the global heat transfer coefficient; T_w and T_t are the workpiece and cutting tool temperature in ^{0}C. Global heat transfer coefficient, h= 1000 kW/m^2 ^{0}C [11] plays an important role converge the tool temperature.

3. EXPERIMENTAL INVESTIGATIONS

The turning operation was carried out on a heavy lathe, (Make HMT, Model- NH- 16). The ultrasonic system consists of major parts like ultrasonic generator (Make- Roop Telsonic SG- 22) of 2 kW power, booster and an acoustic horn or tool holder. The ultrasonic system was mounted on the saddle to carry out the UVAT process. The experimental arrangement is shown in Fig. 1. Workpiece is Titanium alloy, Ti-6Al-4V with diameter 60 mm and length of 500 mm. The cutting tool was a multi layered CVD coated tungsten carbide tool with nose radius 0.8 mm supplied by Widia, India. Both CT and UVAT were carried out alternatively for 80 seconds. The force was measured using KISTLER dynamometer. The results were stored in a computer associated with a Data acquisition system (DAQ). The temperature was measured with a K- type thermocouple, max 6675. The cutting inputs shown in Table 2 were selected based on the literature review and the Widia catalog. A full factorial design with total 9 numbers of run (3*3*1) was incorporated to the experiment with cutting force and tool temperature as the output results.

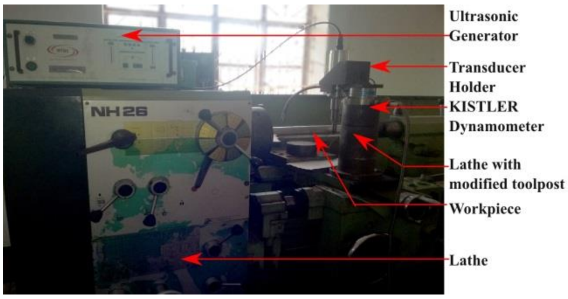

Fig. 1- Experimental set up for turning operation

Table- 2- Cutting control parameters

Symbols	Unit	Parameters	Lv 1	Lv 2	Lv 3
V_c	m/min	Cutting velocity	18	30	40
s	mm/rev	Feed rate	0.04	0.08	0.12
d	mm	Depth of cut		0.22	
f	Hz	Frequency		20000	
a_p	mm	Amplitude		0.045	

4. RESULTS AND DISCUSSIONS

4.1 Average cutting force

The magnitude of average cutting force was noted to reduce significantly, on applying ultrasonic vibration, with an average value of 28.3 % for various cutting velocities varying the feed rates with constant depth of cut of 0.22 mm. Feed rate has similar effect on the cutting force characteristics for both the processes, yet the force generation was lower during UVAT.

4.1.1 Effect of cutting velocity on force

Fig. 2 (a) shows the effect of cutting velocity on the average cutting force for various feed rates at a depth of cut of 0.22 mm. The reductions in force, for instance, at a feed rate, 0.04 mm/rev with constant depth of cut of 0.22 mm were 41.6%, 37.1% and 12.9% for different cutting velocities of 18 m/min, 30 m/min and 40 m/min respectively. The reduction during UVAT process observed for the aerodynamic lubrication at the contact zone due to the intermittent characteristics of the tool . The percentage reduction gradually decreased with the increase in cutting velocity from 18 m/min to 40 m/min. The reason could be the increase in cutting velocity tends towards the critical velocity of the tool tip lowering the tool workpiece contact ratio (TWCR). Therefore, lower cutting velocity is always suitable to carry out the UVAT process as noted by several researchers [2-5].

4.1.2 Effect of feed rate on force

Fig. 2 (b) shows the effect of feed rates on the cutting force for various cutting velocities with constant depth of cut of 0.22 mm. It was noted that feed rate has a direct effect on the force generation for both the cutting processes. However, for constant feed rates, the force magnitude was much lower during UVAT process concluding the process possessing better material removal rate capability. This is due to reason that the intermittent motion reduces the uncut chip thickness generating smooth and thin chip.

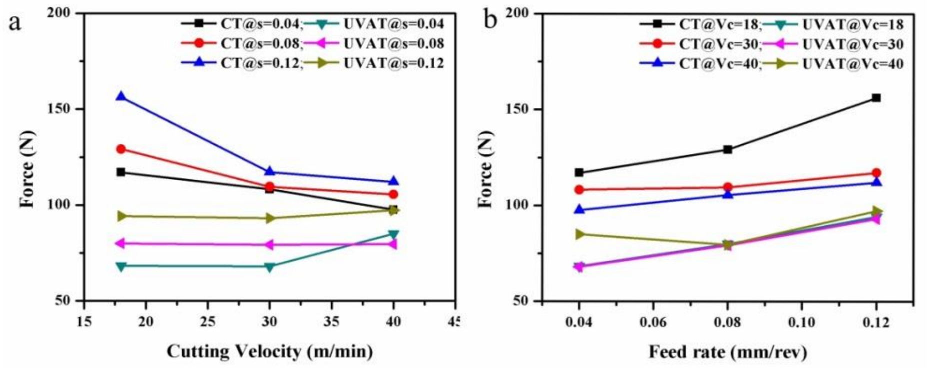

Fig. 2- Effect of (a) Cutting velocity and, (b) Feed rate on average cutting force

4.2 Cutting tool temperature

Cutting tool temperature was measured using a K- type thermocouple firmed near the nose radius with the help of silver brazing that can withstand up to 1000 ^{0}C. The thermocouple was attached to a signal processor, max 6675 which can directly digitalize the voltage signal from the thermocouple. Fig. 3 (a-c) shows the effect of cutting velocity on the average cutting tool temperature. On applying ultrasonic vibration, the tool temperature reduces for almost all cutting combinations compared to the CT process. The reductions were significant during 18 m/min and 30 m/min with lower value of feed rates. The higher value of separation time between the tool and workpiece could be the reason for the temperature reduction. As the cutting velocity increased from 30 m/min to 40 m/min, the temperature during UVAT surpassed the temperature generated during CT diminishing the advantages of UVAT process. The combined effect of both increasing cutting velocity and mechanical vibration increases the heat flux entering the tool tip that surges the tool temperature compared CT process.

Therefore, lower cutting velocities with minimum feed rates and depth of cut, are favorable for UVAT process as far as temperature generation is concerned. From the temperature characteristics, it is evident that feed rate has a direct effect on the tool temperature for both the machining processes.

5. MODEL VALIDATION

The simulation results obtained for cutting condition, V_c= 18 m/min, s= 0.08 mm/rev and d= 0.22 mm for both cutting force and tool temperature were compared with the measured results. The average relative errors for both CT and UVAT were found to be 9.03 % and 7.67 % respectively. Fig. 4 shows the comparative results for forces obtained during experiment and simulation.

Fig. 5 shows the comparative results for cutting tool temperature for both the machining processes. The average relative errors for tool temperature during CT and UVAT were found to be 7.47 % and 13.75 %. The lower value of errors shows the acceptance of the finite element models and the models were found to be good relation with experimental results.

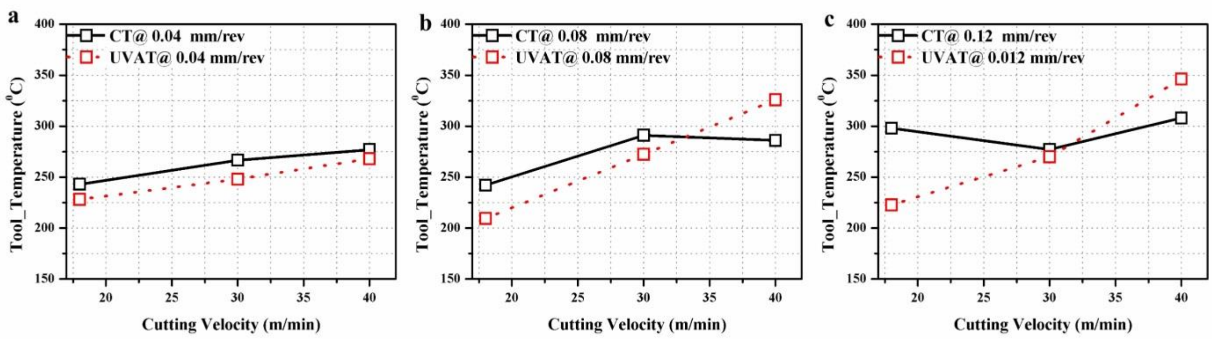

Fig. 3- Effect of cutting velocity on tool temperature at feed rates (a) 0.04 mm/rev (b) 0.08 mm/rev and (c) 0.12 mm/rev

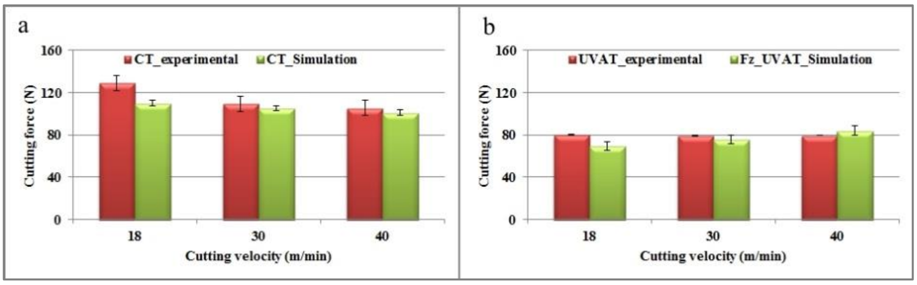

Fig. 4- Comparison of cutting forces (a) during CT and, (b) UVAT

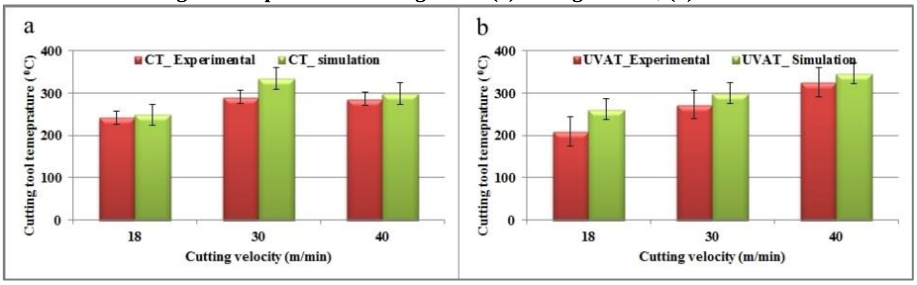

Fig. 5- Comparison of cutting tool temperature (a) during CT and, (b) UVAT

6. CONCLUSIONS

From the above experimental and modelling investigations, the following conclusions can be drawn.

1. Experimental investigation concluded that the UVAT process helped reduce the average cutting force significantly as compared to the CT process. The reduction in cutting force during UVAT was due to the oscillated motion of the cutting tool.
2. Cutting tool temperature was reduced during lower cutting velocities during UVAT showing limitation to this process. As the velocity increased from 30 m/min to 40 m/min, the tool temperature surpassed the temperature generated during CT process.
3. 3D finite element models have been built to understand both the processes using Deform 3D® v 10.0. On comparing the simulation with measured results, the average errors for cutting force were noted to be 9.03 % and 7.67 % during CT and UVAT processes respectively.
4. Further, the average errors for cutting tool temperature were found to be 7.47 % and 13.75 % during CT and UVAT respectively. These results depicts that the model can be accepted predicting stress, strain and interface temperature generation.

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