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Finite Element Modeling of Ultrasonic Assisted Turning of Ti6Al4V Alloy

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Abstract

Improvements in the aviation industry raise the usage of titanium and its alloys. Main reasons of using titanium alloys are superior mechanical properties, high strength-to-density ratio, fatigue and corrosion resistance at moderately high temperatures. All these superior properties comes with a major disadvantage as poor machinability. Machining of titanium alloys generates excessive heat in the vicinity of the tool cutting edge so that induces poor tool life. Cutting parameters of titanium alloys are also limited because of fire risk. Previous studies show that Ultrasonic Assisted Turning (UAT) technique gives promising results at aviation materials. UAT changes the relationship between tool and work piece thus reduces cutting force and temperature on the cutting zone. UAT provides better surface finish and roundness for work piece. In this study, machining of Ti6Al4V alloy investigated by literature review and 2D finite element analysis performed to understand the effects of UAT in turning process. UAT simulation results are compared with conventional turning simulation and experimental results performed by previous studies. It is confirmed that UAT technique alters cutting conditions with specific cutting parameters (cutting force, cutting temperature, chip formation) however, it has some limitations.

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Keywords: Finite Element, UAT, Ultrasonic, Machining, Turning

1. Introduction

Titanium is one of a light metal among the metal materials. Besides the low density, it has excellent strength retaining at elevated temperatures. This considerable point makes the titanium alloys widespread in the transportation industry especially in aviation. As an impressive example, landing gear of Boeing 777 is mainly

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produced from titanium alloys and provides a weight reduction of 270 kg per aircraft compared to the gears made of steel. Furthermore, titanium alloys take part as 7% of Airbus A330/A340 aircraft materials and 33% of common jet engines (Mang, , Bobzin, & Bartels, 2011).

Despite the advantages of titanium utilization, machining of this material has some difficulties. Titanium is chemically reactive and has potential to weld on the cutting tool in the machining. Titanium has low thermal conductivity that cannot dissipate the cutting heat from the cutting zone. Thus, the temperature of contact zone between tool and work piece increases drastically. Increased cutting temperature has negative effects on machining outputs such as reduced tool life and poor surface quality. In addition to this, high strength at high temperatures and low modulus of elasticity are the other drawbacks in the machining of titanium alloys. In the aviation industry, titanium alloys are commonly used in jet engines which are generally cylindrical products. Therefore, turning is the main machining operation for this kind of products. In the airframe applications, milling and drilling operations come into prominence. Moreover; reaming, tapping and sawing are the other conventional operations in the machining process of titanium alloys (Ezugwu & Wang, 1995).

For the refractor materials such as titanium alloys, ultrasonic assisted machining is a solution technology to improve the cutting operation. Ultrasonic assisted machining is based on intermittent cutting of the material. Although, milling or tapping operations are applicable for ultrasonic technology, turning is the best operation to observe the outputs of the process. Therefore, new designed turning operation is called ultrasonic assisted turning (UAT) (Maurotto et al, 2013). Ultrasonic cutting method was first used in 1960s by integrating high frequency vibration onto the cutting tool in conventional method. The method introduced many benefits in the machining operations. The most important gains with respect to the conventional cutting methods are given as; reduced cutting force, reduced cutting temperature, reduced residual stress in the work piece, improved surface quality, improved cylindiricity of turning work piece and improved cutting stability (Nath & Rahman, 2008, Babitsky, Mitrofanov & Silberschmidt, 2004, Babitsky, Kalashnikov & Meadows, 2003, Koshimizu 2009, Mitrofanov, Babitsky & Silberschmidt 2003). These advantages directly develop the quality of work piece. On the other hand, machining equipment is also effectively utilized with this method. Tool life is the main output observed in ultrasonic method studies. It is stated that tool wear under different cutting conditions is reduced up to 80% by applying ultrasonic technique (Sharma, Dogra & Suri, 2008). Tool wear is also observed via surface roughness which deteriorates with increased tool wear. Therefore, studies (Nath, Rahman & Andrew, 2007, Brehl & Dow, 2008, Patil et al 2014) point out 30% to 40% reduction in surface roughness, explain a considerable tool life extension. Ultrasonic method has different parameters such as vibration amplitude, vibration frequency, direction of vibration, natural frequency of the equipment, cutting speed and cutting environment (Patil et al 2014). All these parameters are available for optimizing the operation to achieve the best outputs. In the experimental studies of UAT method, cutting outputs such as cutting temperature cannot be observed instantaneously because of limited data acquisition. However, well-built simulations can provide profound data about the operation. The study contributes the better understanding of Ti6Al4V turning operation with UAT method.

The paper has four parts. First, it reviews the extant literature relevant to machining of Ti6Al4V and UAT method applications. Then the finite element model of UAT operation is presented. Next, simulation results are discussed. The paper concludes with theoretical and industrial implications of UAT method.

2. Finite Element Simulation (FE) of UAT

2D FE model for orthogonal cutting has been developed in DEFORM™. Work piece material of Ti6Al4 was modeled as plastic. Figure 1 shows the system of relative motion between work piece and insert.

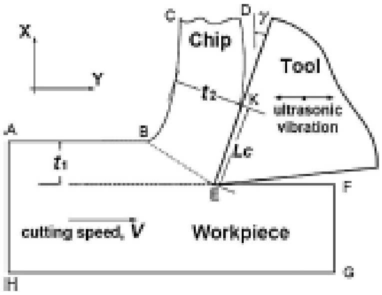

Fig. 1. Relative motion between work piece and insert (Patil et al 2014)

In the simulations, frequency of the ultrasonic vibration was 20 kHz and amplitude was 20 micrometers. Vibration was applied in the direction of cutting speed. Work piece dimensions were 3 mm in length and 1 mm in width. Uncut chip thickness was 0.145 mm. Plain strain conditions were applied.

The number of elements used in simulations was about 3000 for cutting tool 5000 for work piece. Because of the remeshing, the number of elements was increased to 6000 for work piece. In the cutting region, element size was determined about 0.012 mm. In the simulations, X-axis represented the cutting direction and Y-axis represented the feed direction. Boundary conditions of the work piece were determined with respect to the four different cutting speeds. Therefore, the bottom nodes of the work piece were fixed along the Y-axis and driven along the X-axis with the velocity of 10, 20, 30 and 40 m/min. FE model of the simulation is seen in Figure 2.

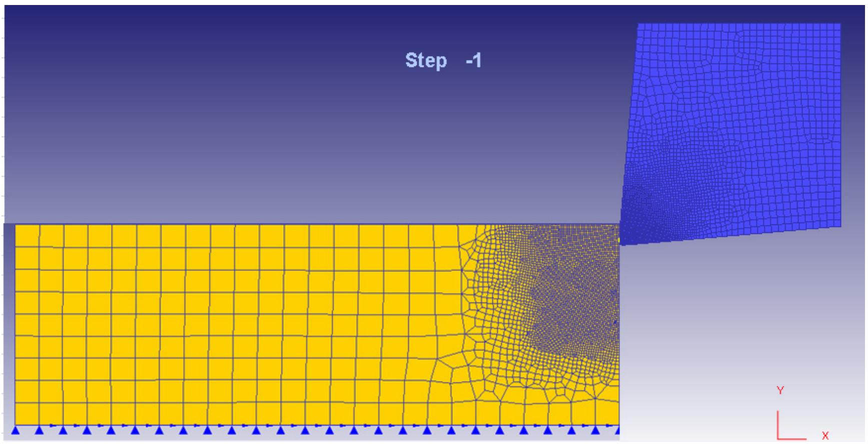

Fig. 2. FE model of the simulation

Table 1. Machining Conditions

Machining Speed	Feed Rate	Depth of Cut	Frequency	Amplitude	Coolant
10 m/min	0.1 mm/rev	0.1 mm	20 kHz	20 µm	Dry
20 m/min	0.1 mm/rev	0.1 mm	20 kHz	20 µm	Dry
30 m/min	0.1 mm/rev	0.1 mm	20 kHz	20 µm	Dry
40 m/min	0.1 mm/rev	0.1 mm	20 kHz	20 µm	Dry

In the simulations, characteristics of the ultrasonic vibration on the tool was explained by harmonic motion. Velocity of the harmonic motion is given below (Babitsky, Mitrofanov, & Silberschmidt, 2004);

$$U_x = -a.\cos wt \quad (1)$$

$$U_y = 0 \quad (2)$$

$$w = 2\pi f \quad (3)$$

where a is the amplitude and f is the frequency of the vibration.

2.1. Work Piece Model

Johnson-Cook (J-C) material model was used to determine the strain rate sensitivity in the simulations. Material parameters used in the simulation are given in Table 1. Values of the parameters were taken from the study performed by Lee (Lee & Lin, 1998).

$$\sigma = \left(A + B\varepsilon^n\right)\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1 - T^*\right)^m \quad (4)$$

$$T^* = \frac{\left(T - T_{room}\right)}{\left(T_{melt} - T_{room}\right)} \quad (5)$$

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

Table 2. Constants of J-C Model suggested for Ti-6Al-4V alloy (Lee & Lin, 1998)

A	B	C	n	m	$\dot{\varepsilon}_0$
724.7	683.1	0.035	0.47	1	2000 s^{-1}

Material model is based on experimental works and curve fitting technique is applied to determine coefficients of Johnson Cook Material model. Using a material model instead of experimental results brings some error in the simulations. In fact, it is too expensive to determine all needed material data experimentally. However, some studies are performed experimentally to improve material models (Sima & Özel, 2010). Required experimental data are obtained by conducting tensile tests to the materials. Tests are performed at different temperatures and strain rates to achieve certain characteristics of the materials. Table 2 shows different coefficient values suggested for J-C Model of Ti6Al4V alloy from previous studies.

Table 3. Constants of J-C Model suggested for Ti6Al4V Alloy

Reference	A	B	C	n	m
Lee & Lin, 1998	782.71	498.4	0.028	0.28	1.0
Lee & Lin, 1997	724.7	683.1	0.035	0.47	1.0
H.W.Meyer & D.S.Kleponis, 2001	862.5	331.2	0.012	0.34	0.8
G.Kay, 2003	1098	1092	0.014	0.93	1.1
S.Seo, O.Min, & H.Yang, 2005	997.9	653.1	0.0198	0.45	0.7

2.2. Cutting Tool Model

Cutting tool was assumed to be rigid in the simulations. Material of the cutting tool was chosen as non-coated tungsten carbide (WC) and the thermal properties were activated in the simulation to observe the thermal effect of the UAT operation. In the geometrical properties of the cutting tool, tip radius was 0.02 mm while side and rake angles were 5°.

2.3. Chip Separation

Fracture criteria has considerable effect on chip separation therefore temperature and cutting force on the cutting zone. It is recommended to employ a failure criteria to observe the certain results in machining simulations. Cockcroft & Latham fracture criterion was selected in the simulations. To observe the effect of failure criteria conventional turning (CT) simulations with 30 m/min were run with and without failure criteria. It was noted that chip shape in the experiments are identical with the chip formation in the simulation with failure criteria. Figure 3 shows the difference between the cutting force and chip formation. It is obvious that serrated chip formation is obtained in simulations with failure criteria while chip shape is smooth in simulations without failure criteria.

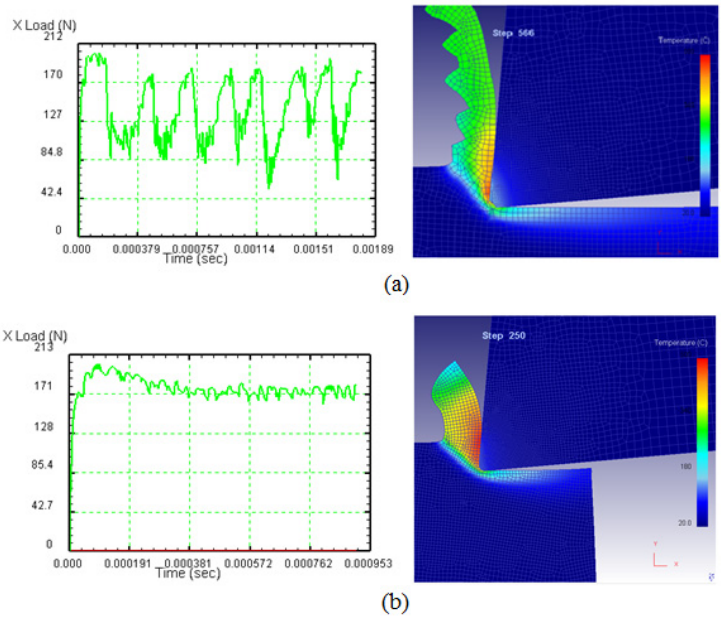

Fig. 3. (a) X cutting force and chip formation with failure criteria (b) X cutting force and chip formation without failure criteria

In the investigation of the chip separation, maximum chip thickness was considered. Simulation and experimental results were compared with a turning speed of 20 m/min and 30 m/min. In the experimental study, chip thicknesses of CT and UAT were measured and values were compared with simulation results. In the operations with 20 m/min, maximum chip thicknesses were measured as 132 µm for CT and 95 µm for UAT, whereas in the operations with 30 m/min, these values were measured as 135 µm for CT and 125 µm in UAT (Patil et al 2014). Good agreement between simulation results and experimental measurements was observed. In simulations, chip thicknesses were observed as 127 µm for CT and 101 µm for UAT in 20 m/min machining while 126 µm for CT and 112 µm for UAT in 30 m/min machining.

3. Results and Discussions

3.1. Cutting Force Prediction

One of the significant advantage of UAT method is reduced cutting force. In UAT technique, reduction of cutting force is obtained by reducing the tool-work piece contact area (Ezugwu & Wang, 1995). Reduced cutting force provides extended tool life and improves surface quality of the work piece. In CT, tool penetrates to work piece and cutting force is only changed in the vicinity of chip separation. Generally stable cutting force is observed during CT operations. However, during UAT operation cutting force oscillates in microsecond intervals. Cutting force during CT and UAT operations with 30 m/min cutting speed are given in Figure 4 and Figure 5.

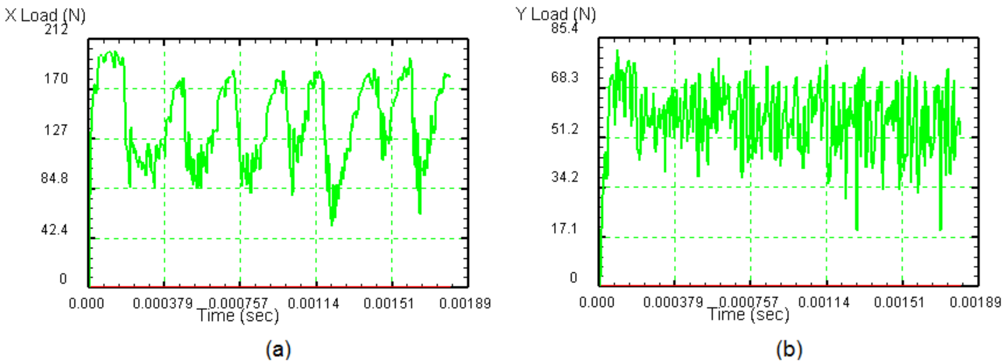

Fig. 4. CT with cutting speed of 30 m/min; cutting force profiles (a) in X-direction (b) in Y-direction

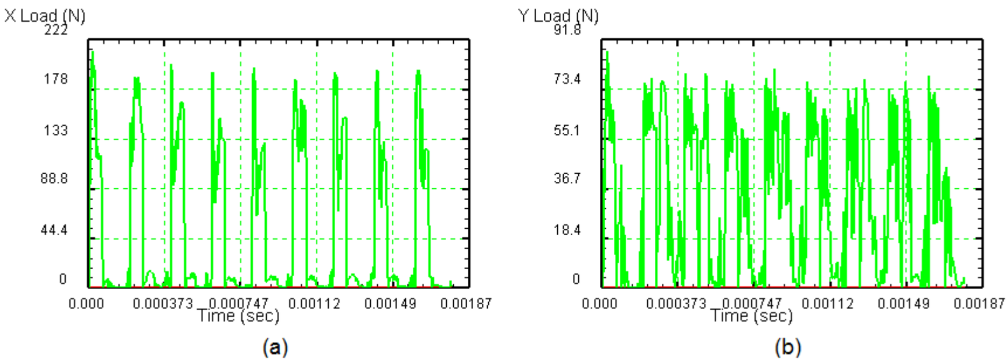

Fig. 5. UAT with cutting speed of 30 m/min; cutting force profiles (a) in X-direction (b) in Y-direction

In the simulation results, the most remarkable difference in average cutting force was observed in the operations with cutting speed of 10 m/min. It was seen that cutting force reduction of 67% in tangential direction was attained in UAT with respect to CT. UAT technique also reduced the radial forces up to 56%. It was also seen that increase in the cutting speed eliminates the advantage of UAT method.

Main advantages of UAT method are obtained in lower cutting speeds. After a certain cutting speed, outputs of the UAT method shows no difference with CT method. This phenomenon is one of the main setback of UAT method and assessed by critical speed. Critical speed is calculated by the formula below;

$$V_c = 2\pi af \tag{6}$$

In this study, critical cutting speed was calculated as 150 m/min for vibrational amplitude of 20 µm and vibrational frequency of 20 kHz. However, it is not effective to set the operation by using the speeds close to the critical speed. At cutting speed of 40 m/min, the difference between CT and UAT reduces to 22,5% in tangential direction and 18% in radial direction by meaning of cutting force. Table 3 shows the cutting forces in CT and UAT operations with different cutting speeds.

Table 4. Cutting forces in CT and UAT simulations

	CT		UAT	
Cutting Speed	F_x (N)	F_y (N)	F_x (N)	F_y (N)
10 m/min	132.51	55.93	43.14	19.97
20 m/min	140.21	56.09	73.90	34.10
30 m/min	131.23	55.83	85.69	42.21
40 m/min	129.22	56.58	100.63	46.87

In the comparison of cutting forces between the reference experimental study (Patil et al 2014) and the simulation results, CT and UAT operations with cutting speed of 20 m/min was assessed. Experimental study showed that 42% reduction in cutting force was observed in UAT method with respect to CT while this reduction was observed as 46% in the simulations. Resultant cutting force was obtained as 190 N in the experiments and 150 N in the simulations for CT operation, whereas 110 N in the experiments and 80 N in the simulations for UAT operation. Figure 6 shows the cutting forces generated in the simulation of CT and UAT operations with different cutting speeds. F_x refers the force in cutting direction and F_y refers the force perpendicular to the cutting direction.

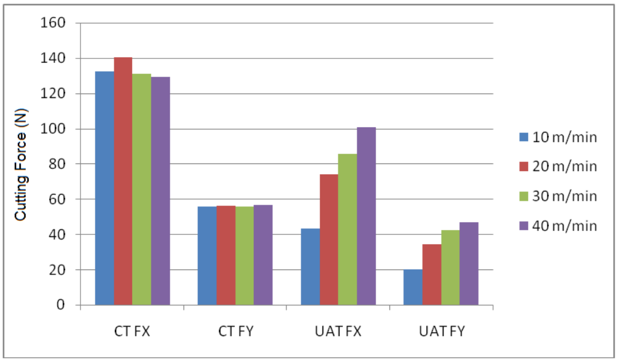

Fig. 6. Cutting force results in the simulations of CT and UAT operations with different cutting speeds

3.2. Cutting temperature

Maximum temperature in UAT operations is observed higher by compared with CT operations. However, motion of the tool retractions in UAT allows some duration to cool down for the tool cutting edge (Muhammad et al 2014). In the simulations of the CT and UAT operations, maximum temperatures during the processes were compared. It is noted that maximum cutting temperatures in UAT operations were higher than maximum cutting temperatures in CT operations for each cutting speed. Table 4 shows the maximum cutting temperatures obtained in the CT and UAT simulations with four different cutting speeds.

However, stability of the cutting temperatures was completely different for each operation. In UAT operations, cutting temperature traced an alternating profile during the process. Maximum temperatures were seen at the peak of these unstable profiles for instant points. Maximum and minimum cutting temperatures were observed in an approximate range of 200^{o}C in UAT operations. On the other hand, CT operations exhibited quite stable cutting temperature profile. Temperature ranges were about 80^{o}C in CT operations. These characteristics of the cutting temperatures proved that maximum temperatures are located at the penetration stage of the tool. Since UAT operations include cyclic motion of the tool, there are successive penetrations during the process which explains the intense peaks of the temperature profile. In CT operations, penetration of the tool is seen at the beginning of the process therefore the strongest peak is seen in this stage. Figure 7 shows the cutting temperature profiles of the CT and UAT operations with cutting speed of 30 m/min. Muhammad et al. (Muhammad et al 2013) explains the temperature increase in UAT by the effect of tool vibration which induces additional energy into the cutting process.

Table 5. Maximum temperatures in simulations

	CT	UAT
Cutting Speed	Max Temperature (°C)	Max Temperature (°C)
10 m/min	385	473
20 m/min	471	610
30 m/min	513	670
40 m/min	547	722

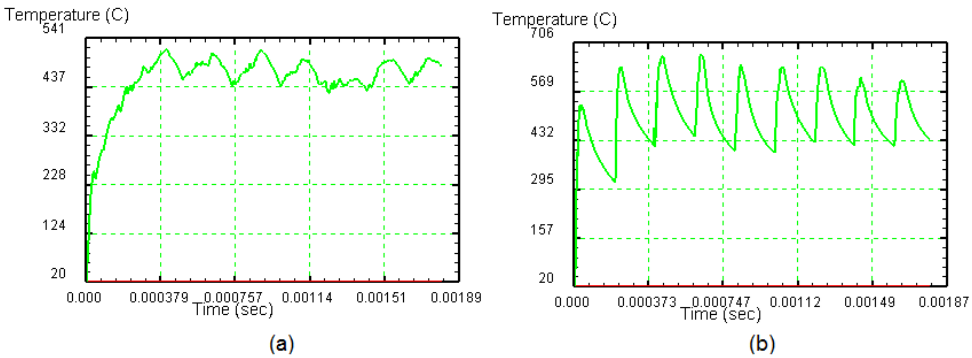

Fig. 6. Cutting3 temperature profiles (a) in CT (b) in UAT operations with cutting speed of 30 m/min

Cutting temperature results in simulations were compared with reference experimental study (Patil et al 2014). Experimental operation with cutting speed of 20 m/min shows the maximum cutting temperature as 442°C while the simulation gives 471°C. In UAT operation with cutting speed of 20 m/min, experimental measurements shows the maximum temperature as 335°C which is quite below of the simulation results of 610°C. In CT operations, stable conditions showed good agreement with the simulation results. But, in UAT operations, unstable characteristics hindered the agreement. It is most probably the measurement error in the experiments that probes could not give quick response at the instant temperature peaks.

4. Conclusion

CT and UAT operations are compared by using experimental data and finite element simulation results. Simulations offer good predictions for real applications of the operations. Good agreements are attained between experimental data (Patil et al 2014) and simulation results. It is seen that CT and UAT have different cutting characteristics in the machining process. Main advantage of the UAT method is achieved as reduction in average cutting force. Cutting force is effective parameter on tool life therefore, increase in tool life is expected in the applications of UAT. Cutting temperature is another considerable parameter in machining that changes in a wide range in the UAT operations. Although maximum cutting temperature in UAT is seen higher than in CT, UAT provides cooling period for the cutting tools by retractions. It is also expected that UAT operations with coolant will allow the coolant to reach the cutting zone effectively. Thus, cooling will be better in UAT than CT. In the future study, effects of coolants can be investigated to cutting outputs. Beside the advantages of the UAT, cutting speed is the main drawback of the UAT operation. As mentioned before, UAT outputs are effective at lower cutting speed. If cutting speed increases, UAT outputs approach to CT outputs. However, improvements in ultrasonic technology can eliminate the cutting speed restriction of the UAT method.

References

Theo Mang, Bobzin Kirsten, & Bartels Thorsten (2011). Industrial Tribology. Weinheim, Germany : Wiley-VCH Verlag GmbH & Co. KGaA.

Ezugwu E.O., & Wang Z.M. (1995), Titanium alloys and their machinability a review. *Journal of Materials processing Technology*, 68, 1995. p.262-274

Maurotto Agostino, Muhammad Riaz, Roy Anish, Silberschmidt Vadim V. (2013), Enhanced ultrasonically assisted turning of a β-titanium alloy. *Ultrasonics*, 53. p.1242-1250.

Nath Chandra & Rahman M. (2008) Effect of machining parameters in ultrasonic vibration cutting. *International Journal of Machine Tools and Manufacture*, 48. , p.965-974

Babitsky V.I., Mitrofanov A.V., & Silberschmidt V.V. (2004) Ultrasonically assisted turning of aviation materials: simulations and experimental study. *Ultrasonics*, 42., p.81-86

Babitsky V.I., Kalashnikov A.N., Meadows A., Wijesundara A.A.H.P. (2003) Ultrasonically assisted turning of aviation materials.. Leicestershire : *Journal of Material Processing Technology*, 132, 2003, p.157-167.

Koshimizu Shigeomi (2009) Ultrasonic Vibration-Assisted Cutting of Titanium Alloy. *Key Engineering Materials*, 389-390, 2009, 277-282.

Mitrofanov A.V., Babitsky V.I. & Silberschmidt V.V. (2003) Finite element simulations of ultrasonically assisted turning. *Computational Materials Science*, 28, 2003, p.645-653.

Sharma V. S., Dogra M. & Suri N M. (2008) Advances in the turning process for productivity improvement – a review. Proceedings of the Institution of Mechanical Engineers, Part B: *Journal of Engineering Manufacture*, 222., 2008, p.1417-1442.

Nath Chandra, Rahman M., & Andrew S.S.K (2007) A study on ultrasonic vibration cutting of low alloy steel. *Journal of Materials Processing Technology*, 192-193. 2007, 159-165.

Brehl D.E & Dow T.A. (2008) Review of vibration-assisted machining. *Precision Engineering* 32 2008, p.153-172

Patil Sandip, Joshi Shashikant, Tewari Asim, Joshi Suhas S. (2014) Modelling and simulation of effect of ultrasonic vibrations on machining of Ti6Al4V. *Ultrasonics* 54., 2014, p.694-705.

Lee Woei-Shyan & Lin Chi-Feng (1998) Plastic deformation and fracture behaviour of Ti–6Al–4V alloy loaded with high strain rate under various temperatures. *Materials Science and Engineering* A241, 1998, p.48-59.

Muhammad Riaz, Hussain Mohammad Sajid, Maurotto Agostino, Siemersb Carsten, Roy Anish, Silberschmidt Vadim V. (2014) Analysis of a free machining α+β titanium alloy using conventional and ultrasonically assisted turning. *Journal of Materials Processing Technology* 214.,2014, 906-915.

Muhammad Riaz, Roy Anish, & Silberschmidt Vadim (2013) Finite Element Modelling of Conventional and Hybrid Oblique Turning Processes of Titanium Alloy *.Procedia CIRP 8*, 2013, p.510-515

Lee W. & Lin C. (1998), High-temperature deformation behavior of Ti6Al4V alloy evaluated by high strain-rate compression tests, *Journal of Materials Processing Technology* 75 1998, p. 127-136

Meyer H.W. & Kleponis D.S. (2001), Modeling the high strain rate behavior of titanium undergoing ballistic impact and penetration, *International Journal of Impact Engineering* 26, 2001, p.509–521

Kay G. (2003) Failure modelling of titanium 6Al–4 V and aluminum 2024-T3 with the Johnson–Cook material model. *U.S.Lawrence Livermore National Laboratory, Report* DOT/FAA/AR-03/57, 2003.

Seo S., Min O. & Yang H. (2005), Constitutive equation for Ti–6Al–4V at high temperatures measured using the SHPB technique. *International Journal of Impact Engineering* 31, 2005,p. 735–754.

Sima Mohammad & Özel Tuğrul (2010), Modified material constitutive models for serrated chip formation simulations and experimental validation in machining of titanium alloy Ti–6Al–4V, - 11 : *International Journal of Machine Tools and Manufacture* 50 2010. p.943-960