

Exploring the influence of constitutive models and associated parameters for the orthogonal machining of Ti6Al4V

S Pervaiz ¹, S Anwar ², S Kannan ³ and A Almarfadi ²

¹Department of Mechanical and Industrial Engineering, Rochester Institute of Technology – Dubai, P.O. Box 341055 Dubai, United Arab Emirates

²Industrial Engineering Department, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia

³Department of Mechanical Engineering, American University of Sharjah, P.O. Box 26666 Sharjah, United Arab Emirates

Abstract. Ti6Al4V is known as difficult-to-cut material due to its inherent properties such as high hot hardness, low thermal conductivity and high chemical reactivity. Though, Ti6Al4V is utilized by industrial sectors such as aeronautics, energy generation, petrochemical and bio-medical etc. For the metal cutting community, competent and cost-effective machining of Ti6Al4V is a challenging task. To optimize cost and machining performance for the machining of Ti6Al4V, finite element based cutting simulation can be a very useful tool. The aim of this paper is to develop a finite element machining model for the simulation of Ti6Al4V machining process. The study incorporates material constitutive models namely Power Law (PL) and Johnson – Cook (JC) material models to mimic the mechanical behaviour of Ti6Al4V. The study investigates cutting temperatures, cutting forces, stresses, and plastic strains with respect to different PL and JC material models with associated parameters. In addition, the numerical study also integrates different cutting tool rake angles in the machining simulations. The simulated results will be beneficial to draw conclusions for improving the overall machining performance of Ti6Al4V.

Keywords Titanium, Orthogonal machining, Finite element, Ti6Al4V

1. Introduction

Titanium and its alloys are referred as difficult-to-machine materials due to their inherent characteristics such as high hot hardness and low thermal conductivity [1,2]. Titanium alloys are employed in different sectors for the aeronautic, structural, biomedical, petro-chemical and energy generation applications etc. [3,4]. In the metal cutting research community, numerical machining simulations gained popularity to predict the machining performance of such difficult-to-machine materials. In addition, numerical modelling techniques provide a cost effective solution and expensive experimentation can be avoided [5]. Several researchers have conducted their research work in the area of developing more precise and reliable numerical machining simulations. Yen et al. [6] executed a numerical simulation based study to investigate different tool edge geometries. The study incorporated several types of edge geometries such as round, honed and chamfered tool edge under orthogonal cutting mode. Cutting temperature, stress and strain were observed for different cases. The study provided a good understanding of the physics involved during the cutting operation, and revealed areas where optimization can improve economic and machining performance. Yang et al. [7] executed a finite element based numerical study to investigate the influence of hydrogen during the machining of Ti6AL4V. The Johnson cook (JC) model was utilized in combination with the quasi-static experimental measurements. The study observed a considerable influence of hydrogen presence on the cutting forces and cutting temperatures. The study revealed that at 0.3% hydrogen, machining



performance outperformed other settings. However, the machining performance was found to be very sensitive with the cutting parameters.

Umbrello et al. [8] performed a study to explore the behaviour of AISI 316L steel by varying Johnson - Cook (JC) model parameters. The numerical simulations provided results towards the cutting forces, temperature at cutting interface, residual stress profiles and chip formation. The numerical findings were validated experimentally as well. It was observed that the processing parameters and residual stresses are very sensitive to the fluctuations of JC parameters. Nieslony et al. [9] investigated the influence of constitutive behaviour of AISI 1045 by using multilayer coated cutting tools. The study utilized power law based constitutive model with special considerations towards thermal softening. The study also compared the new constitutive behaviour with the two already developed models from the literature. The study also pointed out at the different nature of thermal softening models as a major problem towards the standardization of the knowledge. Xi et al. [10] created a finite element based numerical model to study the thermally assisted machining of Ti6Al4V. The study produced simulated chip geometries and respective cutting forces. The numerical findings were found to be in good agreement with the experimental data. The study revealed the link between the multiple shear band formation on the chip and higher oscillation frequency of cutting forces. Arrazola et al. [11] investigated the cutting temperature generation during the metal cutting operation using both experimental and numerical modeling approaches. Cutting temperature is of central importance as the surface integrity and tool life is linked with it. Afsharhaneai et al. [12] performed a numerical study to investigate the formation of dead metal cap during the machining process. The formation of dead metal cap was investigated in reference to the cutting forces, chip morphology, stress formations and cutting temperature.

Some researchers have also dedicated their studies to compare the simulated results from different commercially available codes. Bil et al. [13] compared the machining simulated results obtained from MSC Mark, Deform 2D and AdvantEdge packages with the experimental data. Davoudinejad et al. [14] in a study investigated a chip formation in Ti6Al4V machining under dry and cryogenic cutting environments. Both experimental and numerical investigations revealed better machining performance of cryogenic cooling method in terms of chip formation and cutting forces. The study also complemented the chip segmentation frequency and chip thickness. Davoudinejad et al. [15] in another study conducted a finite element simulation based study on micro end-milling, and investigated the chip flow, bur formation and cutting forces for 6061-T6 aluminium alloy. The bur formation simulated results were found to be in accordance with the experimental findings. However, the simulated estimations of cutting forces were found higher in magnitude than the experimental measurements. Davoudinejad et al. [16] also performed another finite element based study to direct a study towards the cutting tool run out under micro end-milling operation. The study utilized Al6082-T6 and TiAlN-X as workpiece and cutting tool materials respectively. Johnson - Cook (JC) material model was utilized to model the constitutive behaviour of the workpiece material. The model provided good understanding about the tool run out influence in correlation with the chip formation and the cutting forces. Bai et al. [17] performed a study for the ultrasonic assisted cutting of Ti6Al4V. The study was focused towards the microstructure of the machined surface. The model was executed based on the Johnson-Mehl-Avrami-Kolmogorov (JMAK) to predict the dynamic recrystallization behaviour.

Ding and Shin [18] performed a numerical study to investigate the metallo-thermomechanical coupling investigation of AISI 1045 2D machining. The model was provided a very useful interaction of phase transformation with the cutting temperature and chip morphology simultaneously. The simulated results were found in good agreement with the experimental measurements. Kuttolamadam et al. [19] conducted a high-performance computing (HPC) based numerical study to investigate the multi-level multi-variable design approach to facilitate the profitable and optimized machining of titanium. The approach incorporated the influence of input configurations, materials, geometries and processing parameters to investigate highest material removal rate (MRR) with least processing cost. The study incorporated bivariate analysis using SimaFore software. Mamalis et al. [20] performed a numerical study to simulate the high speed hard turning process. The study utilized both orthogonal

and oblique cutting arrangements. The numerical study was conducted using a specialized numerical machining code AdvantEdge. In additional numerical simulations were validated through experiments as well. The study provided useful understanding of the hard-turning process at high cutting speeds with respect to the industrial and practical applications. The study also pointed out at the usefulness of codes such as AdvantEdge in terms of saving time and cost for complex experimentation. The accuracy and reliability of any finite element based simulation is linked with the utilization of precise constitutive material models for the tool and workpiece materials. The current study is aimed on the utilizing two different versions so material constitutive laws based on the power law (PL) and Johnson – Cook (JC) models. Different constitutive parameters were changed and their influence has been reported on different machining parameters.

2. FE Simulations and Constitutive Material Models

Finite element modeling was performed using a specially designed software for machining application known as Thirdwave AdvantEdge. Thirdwave AdvantEdge software uses dynamic explicit lagrangian formulation to simulate chip formation in machining process. The software is capable of executing coupled thermo-mechanical transient analysis and adaptive remeshing techniques [21]. The software was first presented by Marusich and Ortiz [22]. The current study is focused on the 2D modeling of a machining process, where cutting tool was modelled as a rigid material. The schematic illustration of the 2D cutting process has been represented in Figure1.

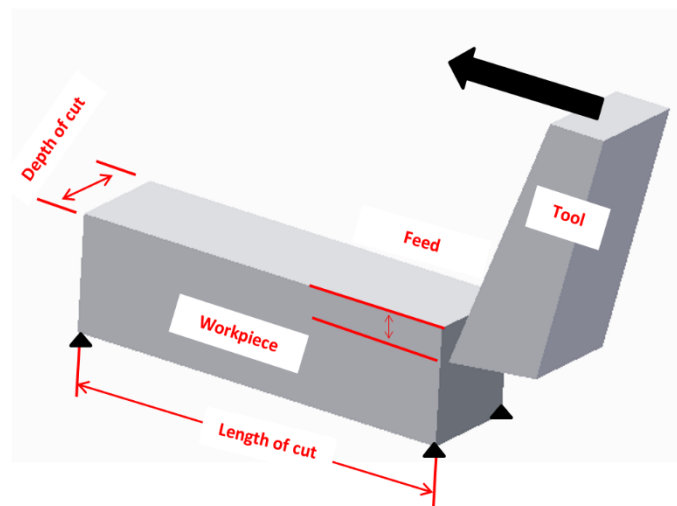


Figure 1: Schematic representation of 2D FE model developed in Thirdwave AdvantEdge

2.1 Power Law (PL) material model

The software has a built-in material models to use for the variety of engineering materials. These material models are capable of simulating flow stresses by incorporating the effects of strain, strain rate and temperature. By default, AdvantEdge software utilizes power law to model the constitutive behaviour of the Ti6Al4V. The constitutive power law can incorporate the effects related to strain hardening, strain rate sensitivity and thermal softening. The power law is mentioned in equation 1.

$$\sigma(\varepsilon^P, \dot{\varepsilon}, T) = g(\varepsilon^P) \Gamma(\dot{\varepsilon}) \Theta(T) \quad (1)$$

Where $g(\varepsilon^P)$, $\Gamma(\dot{\varepsilon})$ and $\Theta(T)$ represent strain hardening, strain rate sensitivity and thermal softening respectively, and the functions are further elaborated in equations 2, 3 and 4 [23].

$$g(\varepsilon^P) = \sigma_0 \left(1 + \frac{\varepsilon^P}{\varepsilon_0^P} \right)^{1/n} \quad (2)$$

$$\Gamma(\dot{\varepsilon}) = \sigma_0 \left(1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^{1/m} \quad (3)$$

$$\Theta(T) = C_0 + C_1 T^1 + \dots C_5 T^5 \quad (4)$$

2.2 Johnson- Cook (JC) material model

In addition to the power law, another constitutive material model namely Johnson – Cook (JC) material model was employed to depict the Ti6Al4V material behaviour. JC model is also composed of three different terms to incorporate the influence of plastic strain, strain rate and thermal effects. Equation 5 represents the JC constitutive model.

$$\sigma = [A + B (\varepsilon)^n] \left[1 + C \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[1 + \left(\frac{T - T_{room}}{T_{melt} - T_{room}} \right) \right] \quad (5)$$

AdvantEdge software utilizes a damage model to incorporate damage into the material model. The damage function D is represented as mentioned in equation 6 [23].

$$D = \sum_i \frac{\Delta \varepsilon_i^p}{\varepsilon_f^p} \quad (6)$$

The friction at the cutting tool and chip interface was modelled using a Coulomb law as shown below in the equation 7 [23]. As per the law the shear stresses are considered proportional to the normal stresses with a frictional coefficient (μ). Table 1 represents the illustration of different parameters and their levels examined in this numerical study. JC material model parameters were selected from the literature [24] and represented in Table 2.

$$\tau = \mu \sigma_n \quad (7)$$

Table 1. Cutting conditions, tool and workpiece material parameters utilized in numerical simulations

	Level 1	Level 2
Cutting Tools	Carbide insert with TiAlN coating (0.004 mm)	
Workpiece Materials	PL material model	JC material model
Rake angle (°)	0	10
Cutting Speed (m/ min)		100
Feed rate (mm/ rev)		0.1
Depth of Cut (mm)		1

Table 2. Johnson Cook (JC) material model parameters [24]

	A (MPa)	B (MPa)	n	C	m
JC Model	782.7	498.4	0.28	0.028	1

3. Simulated Results and Discussion

Orthogonal machining (2D) simulations of Ti6Al4V using TiAlN coated tools were conducted using the design of simulations as represented in Table 1. The simulated results were examined for the different output parameters such as tangential and thrust cutting force components, cutting temperatures, stresses and plastic strains. Cutting temperature was initially investigated in the simulations due to its importance in overall machining process. As shown in Figure 2, it has been observed that average simulated cutting temperatures for the PL material model was relatively higher than the values obtained for the JC material model. For both PL and JC material models, the average cutting temperatures for 0° rake angle were higher when compared with the average cutting

temperatures for 10° rake angle. The higher values of cutting temperature for 0° rake angle can be linked with the increase in friction at tool chip interface due to aggressive mechanical contact. Increasing the rake angle improves the overall machining process by reducing the cutting temperature as observed in the numerical results shown in Figure 2e. The value of m in the JC model controlled the thermal softening phenomenon and provided estimation of cutting behaviour at higher temperatures.

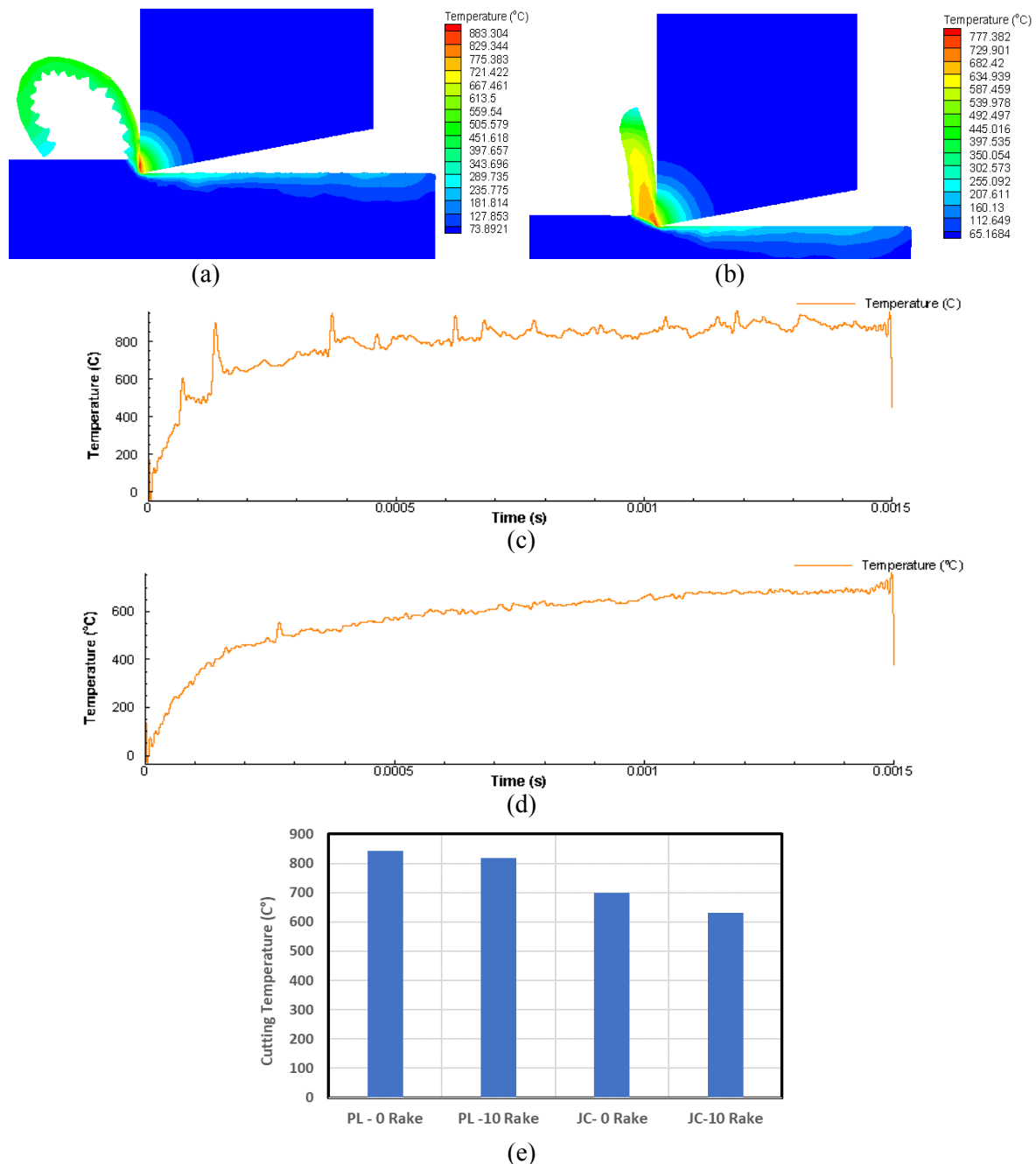


Figure2: Simulated results of the cutting temperature, (a) PL - 0° Rake, (b) JC - 0° Rake, (c) Cutting temperature profile PL-0° Rake, (d) Cutting temperature profile JC - 0° Rake and (e) Average cutting temperatures for all conditions

For both PL and JC material models at 0° rake angle, the maximum and minimum values of the Von Mises stresses have been reported in the Figures 3a and 3b. As expected maximum level of stresses were found to be in the close vicinity of the shear plane and cutting tool tip. In JC model the higher

value of Von Mises stress was found more prominent than the PL model. The dependence of parameter C in JC model deals with the strain rate sensitivity. The values of A, B and strain hardening exponent controlled the flow stress behaviour in the JC model. The aggressive nature of contact in JC model provided higher values of tangential and thrust forces as shown in Figure 3e. The simulated cutting force signatures were reported in the Figures 3c and 3d for both PL and JC models at 0° rake angle. For PL model the tangential and thrust simulated forces were found cyclic in nature and it can be linked with the saw tooth segmented chip formation. Whereas the chip formation was not cyclic and relatively very thick in the JC model. As found in literature, PL model provided more realistic chip formation for the orthogonal machining of Ti6Al4V [25].

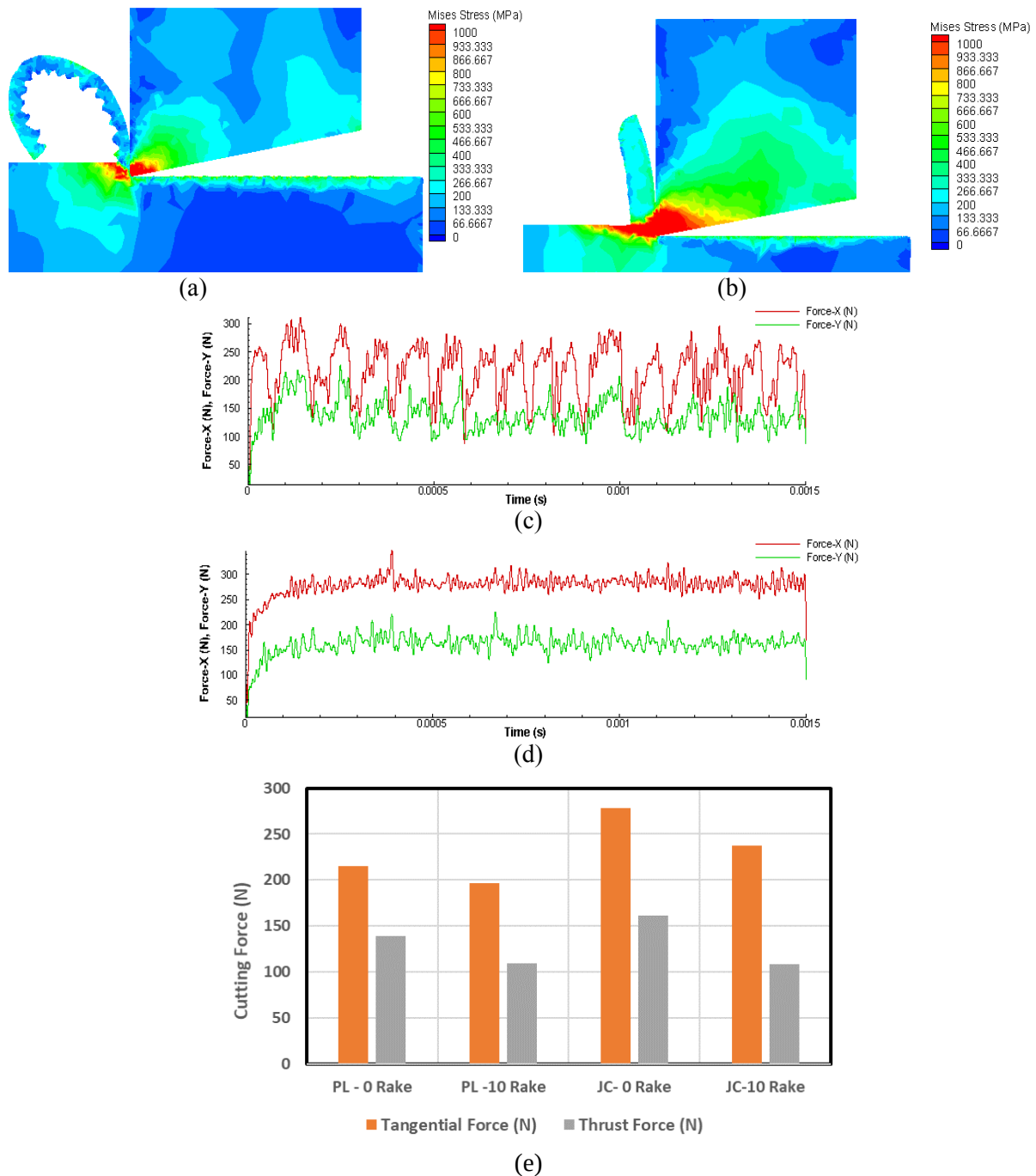


Figure3: (a) Simulated Mises stresses, PL - 0° Rake, (b) Simulated Mises stresses, JC - 0° Rake, (c) Cutting forces PL - 0° Rake, (d) Cutting forces JC - 0° Rake and (e) Average cutting forces for all conditions

Figures 4a and 4b represents the plastic strain observed during the chip formation process for both PL and JC models at 0° rake angle. In both PL and JC material models the plastic strain is maximum at the chip face that rubs against the cutting tool, but it was more prominent in the case of PL. Plastic strain is minimum in the undeformed chip thickness region and increases rapidly after passing through the primary shear zone (PSZ). After crossing the PSZ strain stays almost uniform throughout the deformed chip.

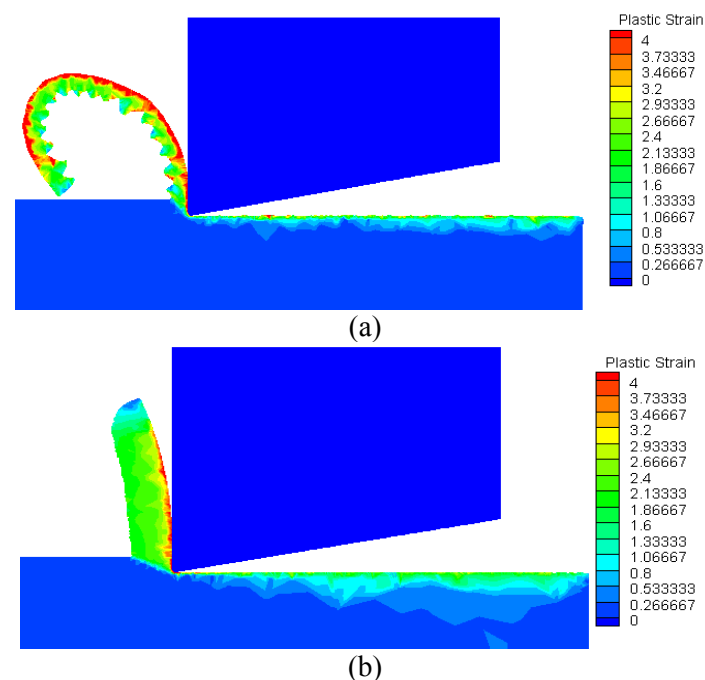


Figure 4: Simulated plane strain results, (a) PL with 0° Rake, (b) JC - 0° Rake

4. Conclusions

The current work is aimed to model the orthogonal machining of Ti6Al4V using two different constitutive material models namely PL and JC models. The simulated outputs were reported and discussed in the form of cutting temperatures, tangential force, thrust force, Von Mises stresses and plastic strains. It has been observed that PL model based cutting simulation provided realistic saw tooth segmented chip formation with associated cyclic tangential and thrust cutting forces. The PL model provided higher values of cutting temperatures when compared to the JC model. For both JC and PL models, maximum plastic strain was observed on the chip face towards the cutting tool and stays uniform after passing through the shear plane.

Acknowledgments

Authors sincerely acknowledge the financial support provided by Dubai Silicon Oasis Authority (DSOA) and Rochester Institute of Technology – Dubai (RIT-D).

References

- [1] Ezugwu E O, Wang Z M and Machado A R 1999 The machinability of nickel-based alloys : a review *J. Mater. Process. Technol.* **86** 1–16
- [2] Ezugwu E ., Bonney J and Yamane Y 2003 An overview of the machinability of aeroengine

- alloys *J. Mater. Process. Technol.* **134** 233–53
- [3] Gorynin I . 1999 Titanium alloys for marine application *Mater. Sci. Eng. A* **263** 112–6
 - [4] Peters M and Kumpfert J 2003 Titanium alloys for aerospace applications *Adv. Eng. Mater.* **5** 419–27
 - [5] Markopoulos A P 2013 Finite Element Method in Machining Processes
 - [6] Yen Y-C, Jain A and Altan T 2004 A finite element analysis of orthogonal machining using different tool edge geometries *J. Mater. Process. Technol.* **146** 72–81
 - [7] Yang S B, Xu J, Fu Y and Wei W 2011 Finite element modeling of machining of hydrogenated Ti-6Al-4V alloy *Int. J. Adv. Manuf. Technol.* **59** 253–61
 - [8] Umbrello D, M'Saoubi R and Outeiro J C 2007 The influence of Johnson–Cook material constants on finite element simulation of machining of AISI 316L steel *Int. J. Mach. Tools Manuf.* **47** 462–70
 - [9] Nieslony P, Grzesik W, Laskowski P and Habrat W 2013 FEM-Based Modelling of the Influence of Thermophysical Properties of Work and Cutting Tool Materials on the Process Performance *Procedia CIRP* **8** 3–8
 - [10] Xi Y, Bermingham M, Wang G and Dargusch M 2013 Finite Element Modeling of Cutting Force and Chip Formation During Thermally Assisted Machining of Ti6Al4V Alloy *J. Manuf. Sci. Eng.* **135** 61014
 - [11] Arrazola P J, Aristimuno P, Soler D and Childs T 2015 Metal cutting experiments and modelling for improved determination of chip/tool contact temperature by infrared thermography *CIRP Ann. - Manuf. Technol.* **64** 57–60
 - [12] Afsharhanaei A, Rebaioli L, Parenti P and Annoni M 2016 Finite element modeling of micro-orthogonal cutting process with dead metal cap *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*
 - [13] Bil H, Kiliç S E and Tekkaya A E 2004 A comparison of orthogonal cutting data from experiments with three different finite element models *Int. J. Mach. Tools Manuf.* **44** 933–44
 - [14] Davoudinejad A, Chiappini E, Tirelli S, Annoni M and Strano M 2015 Finite Element Simulation and Validation of Chip Formation and Cutting Forces in Dry and Cryogenic Cutting of Ti-6Al-4V *Procedia Manuf.* **1** 728–39
 - [15] Davoudinejad A, Parenti P and Annoni M 2017 3D finite element prediction of chip flow, burr formation, and cutting forces in micro end-milling of aluminum 6061-T6 *Front. Mech. Eng.* **12** 203–14
 - [16] Davoudinejad A, Tosello G, Parenti P and Annoni M 2017 3D Finite Element Simulation of Micro End-Milling by Considering the Effect of Tool Run-Out *Micromachines* **187** 1–20
 - [17] Bai W, Sun R and Leopold J 2016 Numerical Modelling of Microstructure Evolution in Ti6Al4V Alloy by Ultrasonic Assisted Cutting *Procedia CIRP* **46** 428–31
 - [18] Ding H and Shin Y C 2012 A Metallo-Thermomechanically Coupled Analysis of Orthogonal Cutting of AISI 1045 Steel *J. Manuf. Sci. Eng.* **134** 51014
 - [19] Kuttolamadom M, Jones J, Mears L, Von Oehsen J, Kurfess T and Ziegert J 2017 High performance computing simulations to identify process parameter designs for profitable titanium machining *J. Manuf. Syst.* **43** 235–47
 - [20] Mamalis A G, Kun-drák J, Markopoulos A and Manolakos D E 2008 On the finite element modelling of high speed hard turning *Int. J. Adv. Manuf. Technol.* **38** 441–6
 - [21] Version A, Software P and Jan B 2006 Third Wave Systems Launches **1** 1–2
 - [22] T.D., Marusich and M. O 1995 Modeling and Simulation of High Speed Machining *Int. J. Numer. Methods Eng.* **38** 3675–3694
 - [23] ThirdWaveSystems 2015 Third Wave AdvantEdge™ User's Manual Version 7.0 378
 - [24] Lee W-S and Lin C-F 1998 High-temperature deformation behaviour of Ti6Al4V alloy evaluated by high strain-rate compression tests *J. Mater. Process. Technol.* **75** 127–36
 - [25] Ducobu F, Rivière-Lorphèvre E and Filippi E 2016 Material constitutive model and chip separation criterion influence on the modeling of Ti6Al4V machining with experimental validation in strictly orthogonal cutting condition *Int. J. Mech. Sci.* **107** 136–49