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Finite element simulation for prediction of cutting forces and chip morphology during in-situ cryogenic micro turning of titanium alloy

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Abstract

In the past few years there is a rise in demand for sustainable micro turned titanium alloy components in the field of aeronautical and biomedical industries. But the major issues in micro turning of Ti-6Al-4V are fluctuations in the cutting force due to saw-tooth chip formation, chip adhesion on the cutting tool due to chemical affinity and high temperature in the tool-chip interface zone due to low thermal conductivity. So the experimental analysis of addressing these issues of titanium alloy are expensive. In view of this, in the present work, a finite element simulations are developed to understand the process mechanics and also to predict the cutting, thrust and feed forces, tool-chip interface temperature and chip morphology during dry and in-situ cryogenic micro turning process. Finite element simulations are developed using updated lagrangian approach by taking into account of edge radius, liquid nitrogen cooling and work hardening effects. A cylindrical heat exchange window is used in the simulation for in-situ cryogenic cooling. Finite element simulations are calibrated for various shear friction factors and finally validated with the forces and chip morphology results measured experimentally. It is inferred that in-situ cryogenic micro turning results in favorable chip formation, less tool-chip interface temperature and minimize the formation of saw-tooth chip which lead to increase the overall accuracy and precision of micro turned titanium alloy implants. However there is an increase in cutting forces when compared with dry machining due to cryogenic cooling and size effects.

Keywords: FEM simulation, Titanium alloy, Micro turning, Cryogenic machining, Cutting forces, Chip morphology

1. INTRODUCTION

Titanium alloy is regularly used as ankle and neurosurgical implants in biomedical applications [1] which are shown in Fig. 1 and 2 respectively This is because of superior biocompatibility when compared to other biomedical materials. However, micro turning of difficult to machine material like titanium alloy is a tough task in aerospace, defense and biomedical industries. The is because of maintaining high specific strength at high temperature which lead to increase energy consumption and tool wear. Another major issue during micro turning of titanium alloy is diffusivity. Titanium alloy reacts with all the cutting tool material at (> 500°C) due to high chemical affinity [2] . A few researchers performed binderless CBN tool to reduce the diffusivity of cobalt with titanium, thereby increasing the life of the cutting tool. Later research reported that adhesion, attrition, dissolution - diffusion are the main wear mechanisms during milling of titanium alloy with binderless CBN tool [3].

Fig.1 Ankle implants[1]   Fig.2 Neuro surgical implants [http://www.neurosurgical.com- Klinefelter pin]

Poly Crystalline Diamond (PCD) tool are effective when compared with other tools because of formation of TiC layer on the rake face of turning insert during macro machining of titanium alloy [4] and hence it is selected as cutting tool for the present work during in-situ cryogenic FEM simulation. Several researchers proposed cryogenic machining is an effective technique for macro machining of difficult to machine material. Umbrello et al. [5] reported that cryogenic machining is superior compared to dry machining of hardened steel. This is due to reduced white layer thickness and better surface roughness. The cryogenic cooling provided in the rake and flank face of cutting tool have less machining temperature during turning of Ti-6Al-4V [6]. Jagadesh and Samuel developed FEM model for prediction of cutting forces during dry micro turning of titanium alloy by taking into account of edge radius and strengthening due to size effect [7]. Rotella et al. developed cryogenic FEM by considering Hall pitch and Zener - Hollomon equation in Johnson Cook workpiece material model for the prediction of grain size and hardness variation [8]. In micro machining, edge radius of the cutting tool and cross sectional area of the chip removal is in the order of micrometer, the high effective stress and heat is concentrated at the tip of the cutting tool which lead to chipping of the cutting edge [9]. So experimental investigation of micro turning of Ti-6Al-4V is expensive.

In earlier literature finite element simulation has been developed for micro turning of ductile material. In this paper, for the first time a finite element simulation is developed for the prediction of forces and chip morphology during in-situ cryogenic micro turning of difficult to machine material i.e titanium alloy. To calibrate and validate the finite element simulation forces, oblique micro turning experiments are carried out at various spindle speeds, feed rate and depth of cut. In addition to this, chip morphology of experiments has been examined in Scanning Electron Microscope and compared with FEM simulations for both dry and in-situ cryogenic micro turning process.

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2. FINITE ELEMENT SIMULATION

Finite element simulations are carried out using DEFORM 3D software for in-situ cryogenic micro turning process. Updated Lagrangian formulation with implicit integration and automatic remeshing technique has been adopted in the present work to solve the problem of high distortion of the deformed mesh in micro turning process which is shown in Fig. 3.

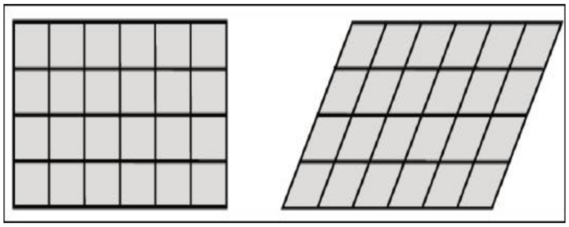


Fig.3 Lagrangian formulation

The accurate prediction of chip morphology, tool chip interface temperature, cutting, thrust and feed forces during in-situ cryogenic micro turning process depends on workpiece material assumption, flow stress, friction between tool-chip-workpiece, thermo mechanical properties of tool and workpiece, heat transfer coefficient between tool-workpiece-chip-environment are explained in the following section.

2.1 Modeling of cutting tool

The micro turning tool is assumed as rigid and workpiece as an elasto-viscoplastic material. The CAD model of PCD tool insert with edge radius is made using SOLIDWORKS and it is imported in DEFORM 3D package. The very fine mesh is specified at the tip of insert and coarse mesh at the remaining portion of the insert which is shown in Fig.4. Trial simulation has been attempted with different element mesh sizes 0.5, 1, 2, 3, 4, 5 and 6 µm and finally 2 µm is chosen which is close to the forces results measured experimentally.

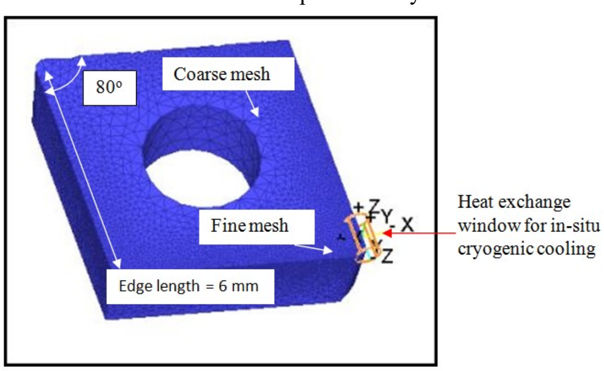


Fig. 4 FEM modeling of micro turning insert with heat exchange window for in-situ cryogenic cooling

The total number of four node tetrahedron elements used to model the micro turning insert is 68963. A cylindrical heat exchange window of diameter 500 µm and length of 1000 µm are used for the simulation of in-situ cryogenic cooling which is shown in Fig.4. Heat transfer coefficient from the tool and workpiece to environment by convection is taken as 20 W/mm^2K [10]. The convection coefficient of liquid nitrogen h_{cryo} from the literature is varying from 5 to 50 kW/ m^2K. A sensitivity analysis has been done with different coefficient and finally 20 kW/ m^2K is selected which is close to the micro turning forces results.

2.2 Workpiece material model

The FEM simulation parameters for in-situ cryogenic micro turning process are given in Table 1. The most widely used model for the prediction of flow stress in macro scale deformation is Johnson Cook material model which is the function of strain, strain rate and temperature. In the present work, modified Johnson - Cook material model with strain gradient plasticity is used to describe the flow stress of the titanium alloy during micro turning process. The flow stress is evaluated using equation (1), (2) and (3).

$$\sigma_{micro} = \sigma\sqrt{1+\left(\frac{18a^2bG^2\eta}{\sigma^2}\right)^{\chi}} \quad (1)$$

$$\sigma = \left[A+B\epsilon^n\right]\left[1+C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]\left[1-\left(\frac{T-T_{room}}{T_{melt}-T_{room}}\right)^m\right] \quad (2)$$

$$\eta = \frac{2\cos\gamma_n}{\sqrt{3}h\cos(\Phi_n-\gamma_n)\sin\Phi_n} \quad (3)$$

where σ_{micro} is the flow stress during micro turning process, η is the effective strain gradient evaluated using Tounsi model [11], h is the thickness of primary shear zone which is taken as 0.5 times of the uncut chip thickness (S_0) [12], Φ_n is the normal shear angle and γ_n is the normal rake angle.

Table 1 In-situ cryogenic FEM simulation parameters

Edge radius of micro turning insert	2 µm
Tool holder: Approach angle Clearance angle	95° 7°
Initial Temperature of workpiece,	20°C
Melting temperature of workpiece,	1660 °C
Shear friction factors (m)	0.80,0.85,0.90,0.95
A ,Yield strength of work material	782.7 MPa
B, Strain hardening Modulus	498.4 MPa
C ,Strain Rate Sensitivity coefficient	0.028
n , Hardening Coefficient	0.28
m, Thermal softening coefficient	1
ε_0 , Reference plastic strain rate	0.00001 s^{-1}
G , Shear modulus	44 GPa
b, Magnitude of burgers vector	0.295 nm
a , Empirical Constant	0.5
χ , Geometric dislocation density	0.38

The total number of four node tetrahedron elements used to model the workpiece material are 100659. The total numbers of nodes per element are 6 and each node has three degrees of freedom. Workpiece movement is arrested at the bottom portion in *x*, *y*, *z* directions and the tool is moving with cutting velocity V_c , which results in chip formation during in-situ cryogenic micro turning process is shown in Fig.5.

2.4 Friction modeling

In general Coulomb friction and shear friction laws are used to describe the friction between tool-chip interface during finite element simulations. If $\mu p_1 \leq m_1 \tau$, then it is considered as sliding friction, otherwise it is considered as sticking friction [10]. Deform 3D automatically detect the contact conditions for an element. In this paper, finite element simulations of in-situ cryogenic micro turning process are carried out with different shear friction factors (m) 0.8, 0.85, 0.9 and 0.95. Finally shear friction factor (m) is taken as 0.95 which is close to the experimental cutting force and chip morphology.

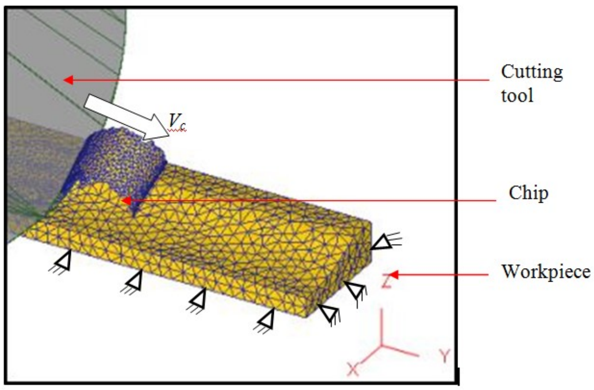


Fig. 5 Finite element simulation along with chip formation during in-situ cryogenic micro turning process

3. EXPERIMENTAL DETAILS

The in-situ cryogenic micro turning setup developed by Jagadesh and samuel [13] at IIT Madras has been used in the present work and the closer view of the setup is shown in Fig.6. Experiments were carried out on titanium alloy of 6 mm diameter using polycrystalline diamond tool of 2 µm edge radius at various spindle speeds [1200, 2400, 3600, 4800, 6000 rpm], feed rate [10, 15, 20 µm/rev] and depth of cut of 30 µm. Based on the diameter of workpiece after each expeiment, the cutting speeds are maintained constant using variable frequency drive.

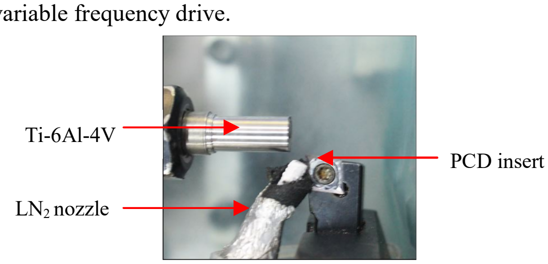


Fig. 6 Closer view of in-situ cryogenic micro turning setup

4. RESULTS AND DISCUSSION

Figure 7 shows the typical variation of cutting, thrust and feed force with time during in-situ cryogenic FEM simulation at 3600 rpm and 30 µm depth of cut. The cutting force is dominant over thrust and feed force which clearly indicate that material undergoes shearing rather than ploughing or rubbing action during in-situ cryogenic micro turning process. The cutting forces acquired from piezoelectric dynamometer during micro turning process are used to calibrate the FEM simulation force results at different shear friction factors. From the sensitivity analysis, 0.95 is selected as shear friction factor which is close to the force results measured experimentally. Figure 8 shows the variation of cutting forces with feed rate at 30 µm depth of cut and 3600 rpm spindle speed. The increase in cutting forces with feed rate is due to an increase of uncut chip thickness and specific cutting energy. Similar trend is observed in both simulation and experimental results. Higher predicted force between micro turning experiment and simulations are due to the cryogenic cooling for the given volume of material removal changes with feed rate in experiments.

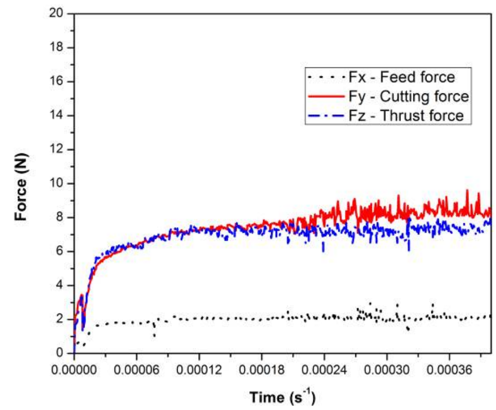


Fig. 7 Forces vs time during in-situ cryogenic FEM simulation

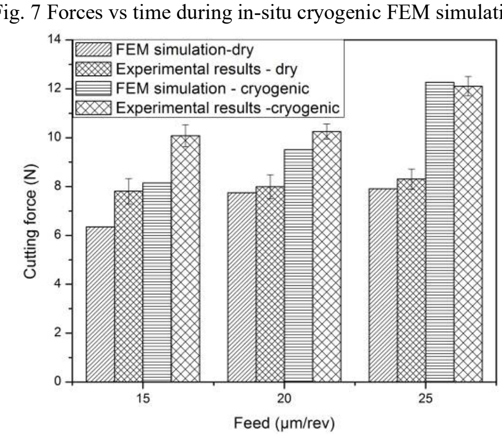


Fig. 8 Cutting forces vs feed rate

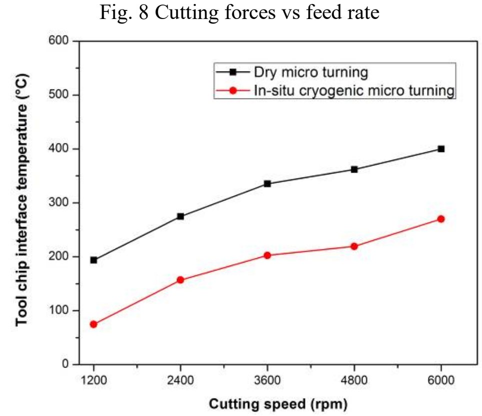
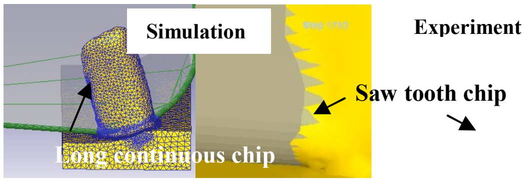


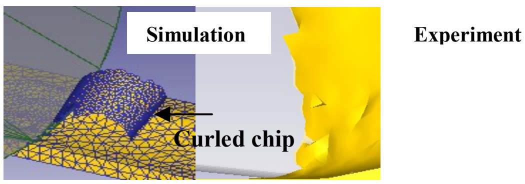
Fig. 9 Tool chip interface temperature vs cutting speed

The difference of tool-chip interface temperature with cutting speed during dry and in-situ cryogenic micro turning of titanium alloy at 30 µm depth of cut and 20 µm/rev feed rate are shown in Fig.9. In-situ cryogenic micro turning results in decrease of tool chip interface temperature, when compared with dry micro turning. This is because of rapid dissipation of heat by liquid nitrogen at -196°C.

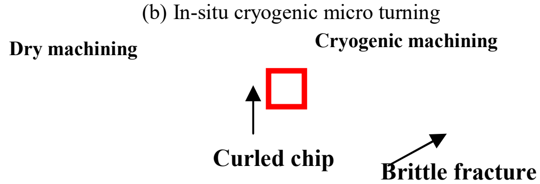
4.1 Chip morphology



(a) Dry micro turning



(b) In-situ cryogenic micro turning



(c) Evidence of brittle fracture of chip

Fig. 10 Comparison of chip morphology at 20 µm/rev feed rate and 3600 rpm spindle speed.

The chip morphology of dry micro turning of Ti-6Al-4V shows long continous saw tooth profile in both simulation and experiments as shown in Fig. 10(a). The saw tooth profile in chips indicates variation in cutting forces. The formation of saw tooth in turning of Ti-6Al-4V is attributed to the crack formation- propagation and thermoplastic shear [14]. The saw tooth wave parameters vary with cutting velocity, uncut chip thicknes and cooling coditions. Saw tooth depth is a function of temperature and hence at low cutting velocity, saw tooth depth is high at the edge and decreases towards the mid of the chip [13]. During dry micro turning of titanium alloy at 3600 rpm the saw tooth depth is more uniform from the beginning to the middle throughout its length as shown in Fig.10(a). Whereas in-situ cryogenic micro turning, discontinuous and curled chip morphology is observed in both simulation and experiments. Low temperature in the shear zone minimizes the formation of saw-tooth chip and is shown in Fig. 10 (b). Figure 10(c) show the experimental evidence of brittle fracture of chips during in-situ cryogenic micro turning of titanium alloy.

5. CONCLUSION

In this paper, a finite element simulations has been developed to understand the in-situ cryogenic micro turning process and to predict the forces, tool chip interface temperatutre and chip morphology. FEM simulations of in-situ cryogenic micro turning process are accurate for predicting the cutting, thrust and feed forces with an accuracy of 90.28, 89.12, 88.30% respectively. The instability of forces in dry micro turning of titanium alloy is attributed to the saw tooth formation whereas during in-situ cryogenic micro turning, LN_2 cooling minimizes the formation of saw-tooth chip and force fluctuations. In-situ cryogenic micro turning results in lesser tool chip interface temperature when compared with dry machining. There is an improvement in the chip formation process during in-situ cryogenic micro turning with an evidence of brittle fracture of chips.

References

[1] H. Hermawan, D. Ramdan, J.R.P. Djuansjah, Metals for Biomedical Applications, 2011.
[2] K.B. Ahsan, A.M. Mazid, G.K.H. Pang, Morphological investigation of Ti-6Al-4V chips produced by conventional turning, International Journal of Machining and Machinability of Materials, 18 (2016) 138-154.
[3] Z.G. Wang, M. Rahman, Y.S. Wong, Tool wear characteristics of binderless CBN tools used in high-speed milling of titanium alloys, Wear, 258 (2005) 752-758.
[4] P.D. Hartung, B.M. Kramer, B.F. von Turkovich, Tool Wear in Titanium Machining, CIRP Annals - Manufacturing Technology, 31 (1982) 75-80.
[5] D. Umbrello, F. Micari, I.S. Jawahir, The effects of cryogenic cooling on surface integrity in hard machining: A comparison with dry machining, CIRP Annals - Manufacturing Technology, 61 (2012) 103-106.
[6] S.Y. Hong, Y. Ding, Cooling approaches and cutting temperatures in cryogenic machining of Ti-6Al-4V, International Journal of Machine Tools and Manufacture, 41 (2001) 1417-1437.
[7] T. Jagadesh, G.L. Samuel, Finite Element Simulations of Micro Turning of Ti-6Al-4V using PCD and Coated Carbide tools, Journal of The Institution of Engineers (India): Series C, (2016) 1-11.
[8] G. Rotella, D. Umbrello, Numerical Simulation of Surface Modification in Dry and Cryogenic Machining of AA7075 Alloy, Procedia CIRP, 13 (2014) 327-332.
[9] D. Dornfeld, S. Min, Y. Takeuchi, Recent Advances in Mechanical Micromachining, CIRP Annals - Manufacturing Technology, 55 (2006) 745-768.
[10] T. Thepsonthi, T. Özel, Finite element simulation of micro-end milling titanium alloy: comparison of viscoplastic and elasto-viscoplastic models, Proc. NAMRI/SME, 41 (2013) 350-357.
[11] N. Tounsi, J. Vincenti, A. Otho, M.A. Elbestawi, From the basic mechanics of orthogonal metal cutting toward the identification of the constitutive equation, International Journal of Machine Tools and Manufacture, 42 (2002) 1373-1383.
[12] S. Rao, M.S. Shunmugam, Analytical modeling of micro end-milling forces with edge radius and material strengthening effectS, Machining Science and Technology, 16 (2012) 205-227.
[13] T. Jagadesh, G.L. Samuel, Mechanistic and Finite Element Model for Prediction of Cutting Forces During Micro-Turning of Titanium Alloy, Machining Science and Technology, 19 (2015) 593-629.
[14] Z.P. Wan, Y.E. Zhu, H.W. Liu, Y. Tang, Microstructure evolution of adiabatic shear bands and mechanisms of saw-tooth chip formation in machining Ti6Al4V, Materials Science and Engineering: A, 531 (2012) 155-163.