Finite Element Modeling and Simulation of Residual Stresses, Cutting Forces and Temperature in Orthogonal Machining of Titanium Alloy.

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ABSTRACT

Structural defects and the stresses to which the structure is exposed affect the life of the structure. These stresses arises from a combination of operational and manufacturing processes, the later hereafter is referred to as residual stresses. However, the correlation of residual stresses with machining parameters is not well understood, especially for high speed machining of titanium. This paper presents the results of finite element modeling, simulation and prediction of residual stresses and cutting forces in orthogonal turning of TI-6Al-4V titanium work piece used in aerospace manufacturing. Finite element modeling and simulation were performed using Third Wave Systems AdvantEdge software. The effect of speed at constant feed and rake angle were investigated. The residual stress prediction as a function of speed and depth from the workpiece surface are presented. Tool temperature, power, cutting and feed forces are also presented. The results show that residual stresses are predominantly tensile on the surface and predominantly compressive below the surface, and both decrease with increase in cutting speed and depth below the workpiece surface. The main cutting and feed forces increases with length of cut until it reaches a steady state. Tool temperature follows the same pattern as the main cutting force.

1 INTRODUCTION

The demand for better surface quality has lead to the study of residual stresses on machined structures. Residual stresses in machined surface result from temperature gradients at the surface and the plastic deformation involved in surface formation, and changes in the microstructure. Residual stresses in a machined surface are vital element in determining surface integrity. Machined structures for the aircraft require high fatigue strength and high resistance to corrosion. The effects of residual stress can be either beneficial or detrimental, depending upon the magnitude, sign or distribution of stress with respect to the load–induced stresses. Studies have shown that surfaces of machined structure has tensile residual stresses which can lead to microcrack formation at the machined surface and reduce the fatigue strength of the components part [1-2]. The presence of residual stress affects stress corrosion cracking of a machined component. Residual stresses can be reduced by reducing plastic deformation, frictional heating, and temperature gradients at

the tool-workpiece, which could be done by reducing cutting speed, applying flood cooling, and avoiding the use of dull tools. Excellent fatigue performance is reported when high compressive residual surface stresses are combined with smooth defect free surface. The knowledge and understanding of effects of cutting parameters such as cutting speed, feedrate, depth of cut on surface integrity is highly important for quality machined surface [3]. Residual stresses on machined surface have been studied by many researchers. Jang et al [1] conducted studies on residual stress by turning AISI 304 austenitic stainless steel. The study focused on residual stress as a function of machining parameters such as speed, feedrate and tool geometry. X-ray diffraction technique was used for the residual stress measurement. The results showed that increasing tool sharpness leads to a reduction in the level of the surface residual stress for low values of feedrates. Segawa et al [2] investigated the feasibility of developing a new tool called

Compressive Residual Stress Generating Cutter, (C.R.S.G) that can generate compressive residual stress within machined surface by means of milling operation, thereby increasing the fatigue life of the machined components. Residual stresses measured were found to be between -100 and -200 MPa on the workpiece surface and between -300 to -400MPa at 0.05 mm within the work piece surface. Saoubi et al [3] investigated residual stresses induced by orthogonal cutting of standard and resulfurized austenitic stainless steels using x-ray diffraction technique under different cutting conditions, tool geometries, and tool coatings. Tensile residual stress of about 800MPa was observed on the work piece surface. Shet and Deng [4] used finite element method to simulate and analyze orthogonal metal cutting process under plane strain conditions with focus on residual stress in finished work pieces. The workpiece considered was AISI 4340. To model the effect of contact friction along the tool-chip interface, a modified coulomb friction law was used. The finite element mesh was composed with 1160 four-node plane strain elements with 1308 node. The process consisted of four stages which were steady state, tool removal, boundary removal and cooling stage. It was concluded that the dominant residual stress was tensile along and immediately below the finished surface. When the coefficient of friction is high or when the rake angle is small, the residual stress was slightly compressive or nearly zero. The residual stresses were observed to be moderately affected by the cooling down processes. Sasahara et al [5] used finite element method to develop a process model and investigated the effects of corner radius and feedrates in a face turning process. Their results showed that residual stresses changed from tension to compression as feedrate decreases and as the corner radius become smaller. Hua Fuh and Fu Wu [6] presented a mathematical model for predicting residual stress as a function of cutting parameters and tool geometries in the milling of aluminum alloy and used experimental design approach known as Response Surface Methodology (RSM) with Taguchi method to investigate the effects of process parameters on residual stress. Marusich and Askari [7] modeled residual stress and work piece quality in machined surfaces in orthogonal cutting of Al 7050 using finite element modeling method. A validated finite element-based machining was

employed to determine the effects of cutting process parameters. AdvantEdge metal cutting software was used to perform the simulation. Tests were conducted on a round bar of Al7050 via end turning. The investigation showed that the magnitude and sign of the state of stress have no observed relation to speed, chip load and stress induced bending moment. Sridhar *et al* [8] studied residual stress variation in titanium alloy, IMI-834 following milling at different feeds, speeds and depth of cuts. Hot-rolled, solution-treated and ground picked 50mm diameter bars were machined into 38mm x 25mm x 15mm rectangular test pieces. In order to remove the residual stresses induced, the test pieces were stress-relieved by keeping them at $600^{o}C$ for 1 hour in a vacuum furnace following an argon gas quench. The machining operations were implemented on a FN-2V HMT milling lathe, 5HP capacity, using a T Max K-20 face milling cutter of 50 mm diameter and four TN-35-M titanium nitride coater inserts. It was concluded that at low speeds residual stresses were found to decrease with increase in feed but at high speeds it increases with increase in feed. The magnitude of the compressive stresses increased with increase in cutting velocity and decreased with the increase in the dept of cut. Outeiro *et al* [9] investigated the influence of tool material on induced residual stresses in the work piece. They considered three major sources for residual stresses, which are the cutting force components, the thermal energy dissipated by the workpiece and possible phase transformation in the surface layer. Round bars of AISI 1045 steel were used to conduct the experiments. Two tools were selected with the same geometry but one was coated and the other was uncoated for conducting the experiments. All tests were performed on a 35KW lathe. Cutting forces were measured using a Kistler type 9255B three-component piezoelectric dynamometer. The residual stress state in the machined layers of the workpiece was detected using X-ray diffraction equipment, equipped with a linear detector. It was concluded that the machined workpieces shows that machining with coated tool induced the most critical residual stresses compared with uncoated tool. Titanium alloys due to their unique and excellent combination of high strength to weight ratio and their resistance to corrosion is an attractive material in aerospace industries. However, titanium and its alloys are difficult to machine materials because of its low

thermal conductivity and high chemical reactivity. In this paper, a lagrangian finite element modeling method is applied to model and predict residual stresses and cutting forces, power and tool temperature in orthogonal machining of Ti-6Al-4V titanium alloy,. Through finite element modeling, optimal cutting conditions for titanium alloys with aim of minimum induced residual stress and reduced likelihood of costly mistakes can be achieved.

2. FINITE ELEMENT MODELING APPROACH

In this paper, a Lagrangian finite element-based machining model is applied in the modeling and simulation of residual stresses, cutting forces, and temperature in two-dimensional orthogonal cutting of titanium TI-6Al-4V alloy. The modeling and simulations were conducted using Third Wave Systems AdvantEdge machining simulation software which integrates advanced finite element numerics and material modeling for machining. The technique also integrates techniques such as adaptive remeshing, explicit dynamic and couple transient thermal analysis into modeling metal cutting processes. Figures 1, 2.1 and 2.2 below show the orthogonal cutting process that was used in the modeling. The cutting parameters used for the study of residual stresses, cutting forces, cutting powers and peak tool temperatures are shown in table 1.The simulation was conducted with coolant on, the initial room temperature was fixed at 20.00°C. Cutting edge radius, rake and clearance angle of 0.795mm (0.03 inches), 5° and 10° respectively
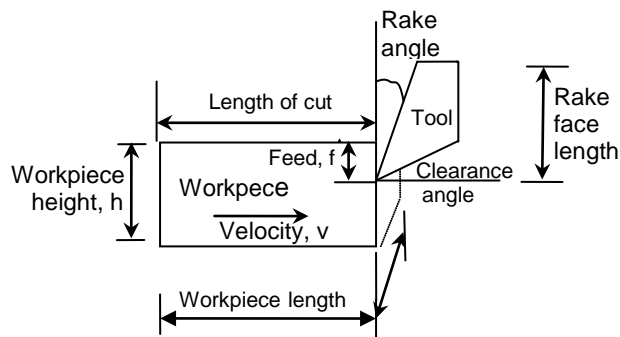
were used. Feedrate was fixed at 0.38mm/rev which was within the recommended feedrates range for turning titanium alloys**.** The cutting tool type and depth of cut used for the simulation were single-point carbide grade-K and 3.81mm respectively. The tool was uncoated. The minimum and maximum element sizes were between 0.02 to 0.1mm while the maximum number of nodes used was 120,000.The output frame was fixed at 30 and the number of cut was one. The cutting speed was the only cutting condition that was varied. The variation of the cutting speed was between 100 and 1000m/min. The workpiece was fed with a cutting speed (velocity), v moving against the direction of the tool. The cutting tool is parameterized by a user-defined geometry and cutting edge radius. Initially, the tool indents the work piece and presents an undeformed mesh structure as shown in figure 3.1. As the tool feeds into the work piece while machining and at a certain depth of cut, the initial mesh becomes distorted, as shown in figure 3.2 and after machining, it is remeshed into its normal mesh structure. The model allows thermo-mechanical recuperation of the workpiece after the machining process. Mechanical vibrations are also allowed to damp out. The residual stresses can be modeled in standard or rapid mode. Residual stresses were modeled in standard mode for better and accurate results. The dynamic and transient heat conduction ability of the software makes it possible to model cutting conditions accurately.
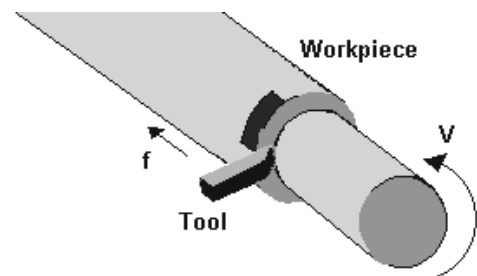

Figure 2.1.Schematic diagram showing the workpiece and tool.

Figure 1. Schematics diagram used for the turning process.

Exp	Rake angle (deg)	Feed (mm/rev) [lpr]	Speed (m/min) [fpm]
1	5	0.38 [0.015]	100 [328]
2	5	0.38 [0.015]	200 [656]
3	5	0.38 [0.015]	300 [984]
4	5	0.38 [0.015]	400 [1312]
5	5	0.38 [0.015]	500 [1640]
6	5	0.38 [0.015]	600 [1969]
7	5	0.38 [0.015]	700 [2297]
8	5	0.38 [0.015]	800 [2625]
9	5	0.38 [0.015]	1000 [3281]

Table1: Experimental design used for the analysis in the turning of Titanium alloy (Ti-6Al-4V) at varying cutting speed

Tool
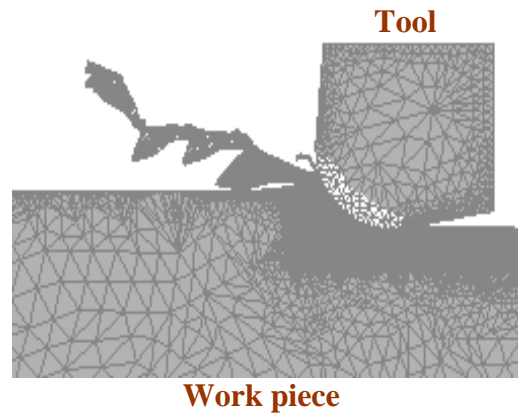
Work piece

Figure 3.2.Distorted mesh structure and chips formed during cutting.

Residual stresses are predicted in the workpiece as a function of depth and the cutting parameters modeled. Residual stresses can be measured along three directions; radial, circumferential and axial direction. Previous works done in turning have shown that cutting and feed forces supplies more energy or engaged in greater part of a cutting operation than the radial force. Residual stress measured along the radial direction can be neglected when compared to that along the circumferential or tangential and axial direction. Below in figure 4 is a diagram showing cutting and residual stress directions relative to the work piece. Figure 5.1 shows the forces acting on the tool, namely, cutting force, $F_{cutting}$, feed force, F_{feed}, and radial force, F_{radial}.
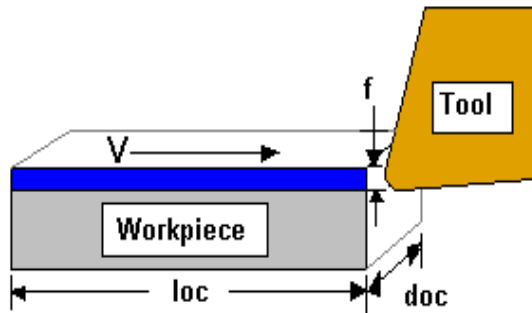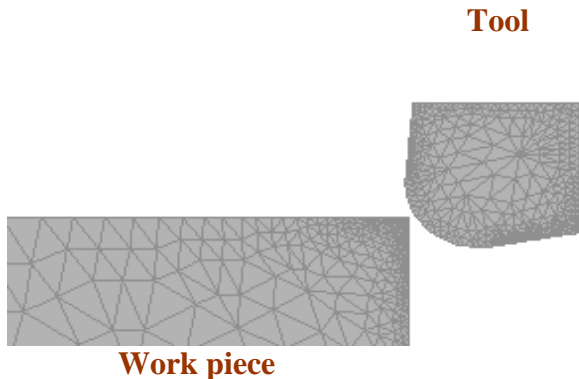

Figure 2.2. Schematic diagram showing simulation model.

Tool

Work piece
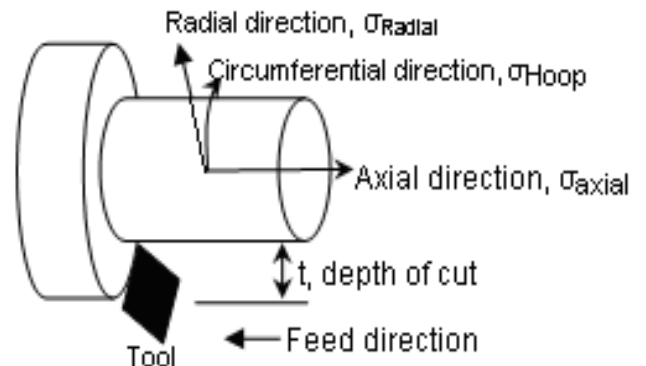
Figure 3.I.Initial mesh structure and tool indentation

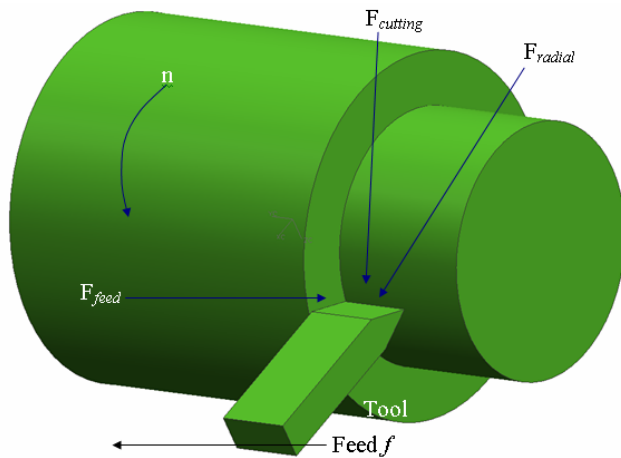Figure 4. Cutting and Residual Stress direction relative to work piece

Figure 5.1The forces acting on a tool; F$_{cutting}$, cutting or tangential force, F$_{feed}$, thrust or feed force and F$_{radial}$, radial force.

3 RESULTS AND DISCUSSIONS

3.1 Residual Stress as a Function of Depth from Workpiece Surface

The residual stress measurement was carried out along the circumferential direction (σ_{hoop}). Residual stress was plotted as stress units (MPa) and as a function of the distance from the surface of a machined workpiece towards the center (mm).The residual stress extraction was done by one line at 50% of the length of cut of machined surface. The extraction can also be carried out as an average of three lines (extraction at 25%, 50% and 75%) of machined surface. Figure 5.2 below illustrate the lines of residual stress extraction.
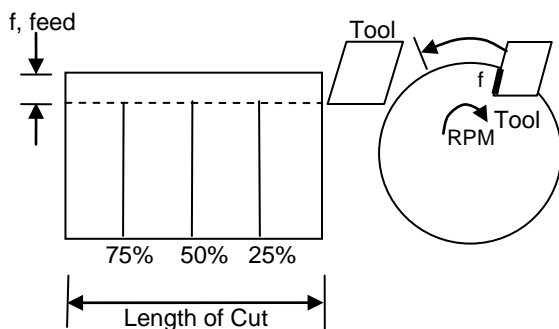
Figure 5.2. Lines of residual stress extraction.

The plots of residual stresses as a function of depth into the work piece obtained at varying cutting speeds of between 100m/min and 1000m/min are presented in Figure 6.1 to 6.5. The plots show the residual stress to be tensile at the surface of the work piece and become compressive at about 0.1mm into the workpiece and thereafter reverse to tensile residual stress till about 1mm beneath the work piece surface before reversing again to compressive residual stress at about 2.8mm into the workpiece. With increase in cutting speed from 100m/min to 1000m/min, the predicted surface tensile residual stress decreased from 600 to 350 MPa.
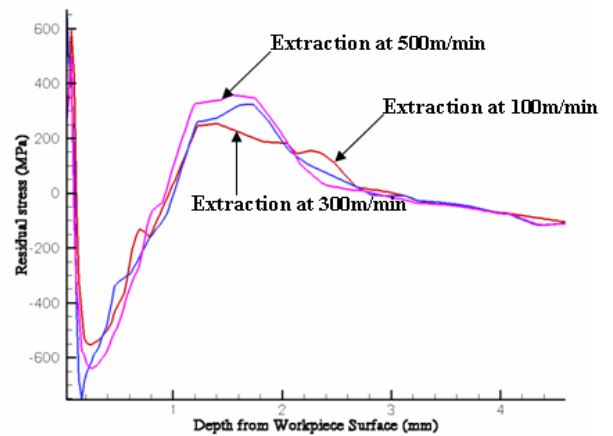

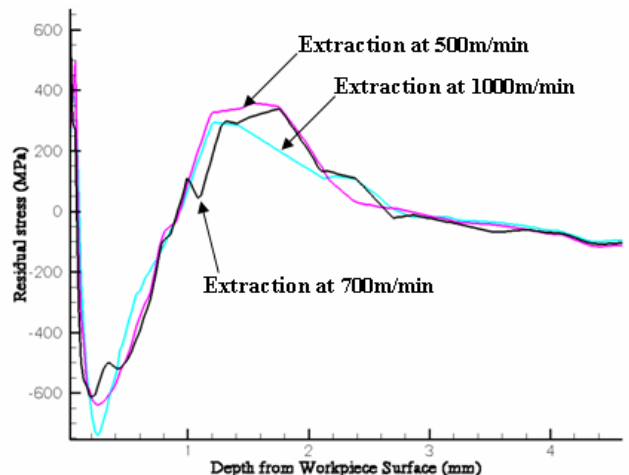Figure 6.1.Residual stress versus depth from work piece surface at 100, 300 and 500 m/min.

Figure 6.2. Residual stress versus depth from work piece surface at 500, 700 and 1000m/min.

3.2 Effect of Cutting Speed on Tangential Force, Feed Force and Tool Temperature.

Figure 7.1 to 7.5 below shows the combined plots of cutting force, F_Y, feed force, F_X, and peak tool temperature in degree centigrade.
Cutting forces in x and y directions and peak tool temperatures were obtained at varying speeds of between 100m/mins and 1000m/min.The force in the direction of cutting is known to be the cutting force, F_Y and that force along the feed is known to be the feed force, F_X. Both forces were predicted in Newton while the temperature was predicted in degree centigrade. Predicted cutting forces in the Y direction were observed to be greater than that in the X-direction in all cases of varying the spindle speed. Both forces increase with length of cut until they reach a steady state. The maximum predicted cutting force and feed force were approximately 8100 and 4100 Newton respectively at 100m/min.
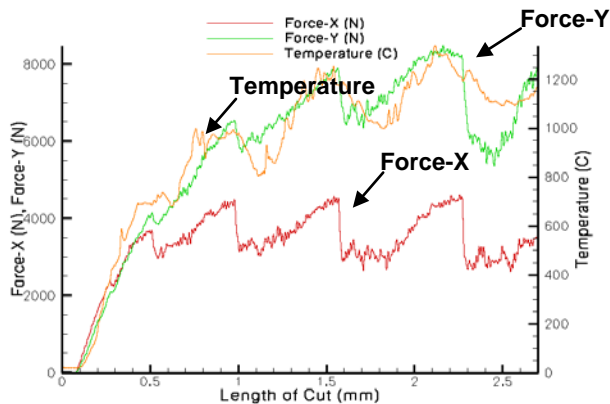

Figure 7.1. Forces in X, Y direction and Tool Temperature as a function of length of cut at 100m/min.
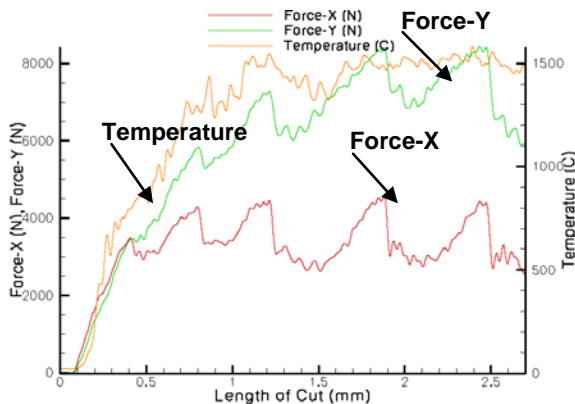

Figure 7.2. Forces in X, Y direction and Tool Temperature as a function of length of cut at 300m/min.
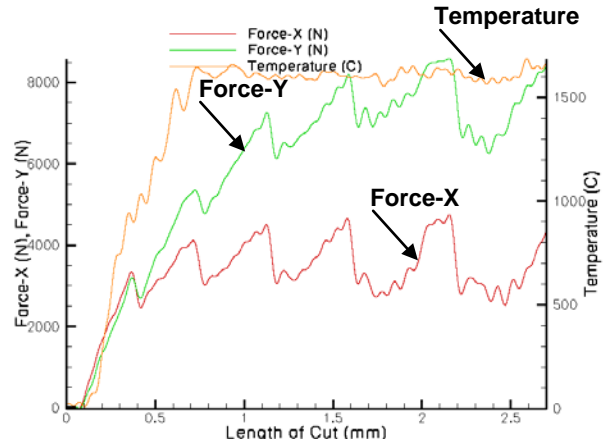

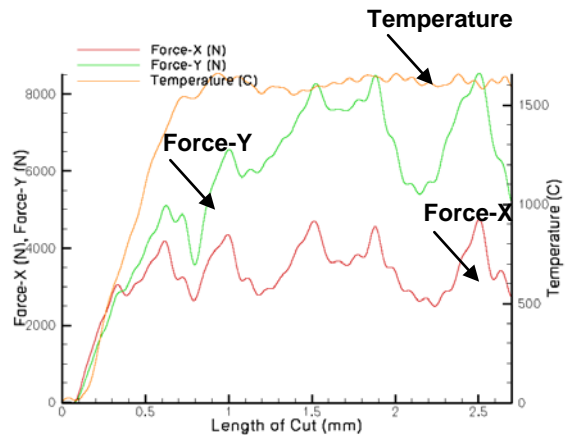Figure 7.3. Forces in X, Y direction and Tool Temperature as a function of length of cut at 500m/min.

Figure 7.4.Forces in X, Y direction and Tool Temperature as a function of length of cut at 700m/min.
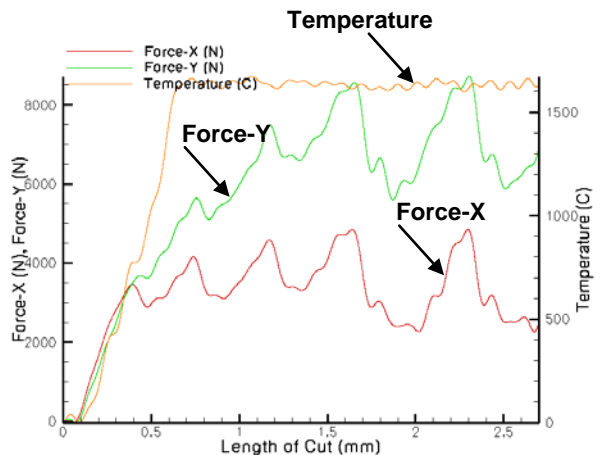

Figure 7.5. Forces in X, Y direction and Tool Temperature as a function of length of cut at 1000m/min.

The predicted tool temperature followed the same pattern as the main cutting force. Temperature was observed to increase as the cutting speed increases. At 100m/min, the temperature was predicted to be approximately 1350 degree Centigrade while at 1000m/min, it was predicted to be approximately 1690 degree Centigrade. Figure 8 shows the plot of the peak tool temperature versus cutting speed. There was a rapid increase in tool temperature between 100m/min and 400m/min to 1600 degree Centigrade. Between 400m/min and 1000m/min, it fluctuates along a steady state of temperature value of 1690 degree Centigrade.

Residual stress plot as a function of cutting speed at a depth of 4mm from the workpiece surface is shown in figure 9. The predicted residual stress graphs shows an increase in compressive residual stress from -71 to -78 MPa when the cutting speed increased from 100m/min to 200m/min and decreased from -78MPa to -62 MPa when speed is increased further to 1000 m/min. Figure 10 show the cutting and feed force plot as a function of cutting speed. Cutting forces at the peak values in the Y direction was observed to increase from 100m/min to 500m/min, decreased between 500m/min and 600m/min, and increased thereafter as cutting speed increases. Feed forces at the peak values in the X direction were observed to decrease between cutting speed of 100 to 300 m/min and increased gradually thereafter till 1000m/min. The plot of the cutting power as a function of cutting speed is presented in Figure 11. Predicted cutting power increases as the cutting speed increases for all cases. The cutting power was observed to be about 8,500 Watts at 100m/min and 81,300 Watts at 1000m/min. Experimental investigations are currently being conducted with same cutting conditions used for the finite element modeling and simulation to verify the simulation results.
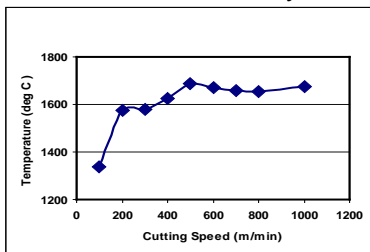

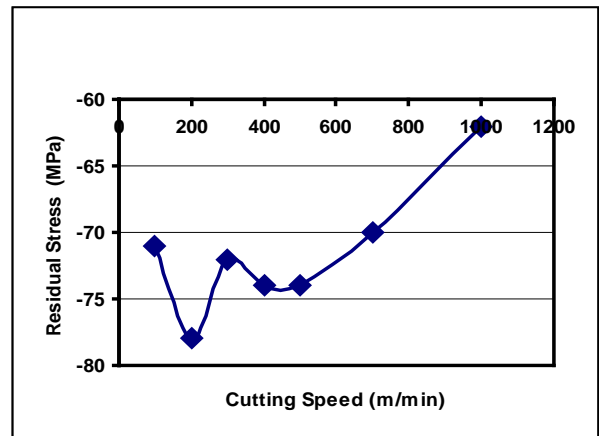Figure 8. Tool Peak Temperature versus Cutting Speed.

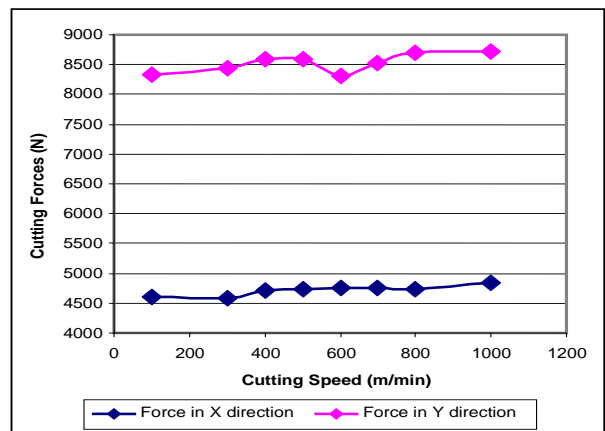Figure 9. Residual stress versus Cutting Speed at a depth of 4mm from the workpiece surface.

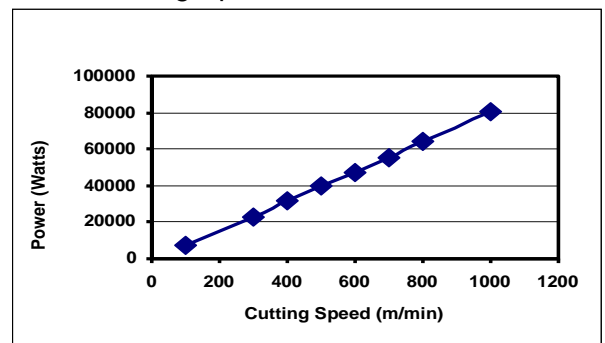Figure 10. Cutting Forces in X and Y-direction versus Cutting Speed.

Figure 11. Cutting Power versus Cutting Speed.

4 CONCLUSIONS

Finite element modeling, simulation and prediction of residual stresses, cutting forces, power, and temperature in orthogonal turning of TI-6Al-4V titanium work piece used in aerospace

manufacturing have been performed using Third Wave Systems AdvantEdge software. From the results, the following conclusions can be made.

1. Tensile residual stresses are induced at the machined surface of the workpiece which become compressive residual stresses after about 0.1mm depth into the workpiece and thereafter reverse to tensile residual stress till about 1mm beneath the work piece surface before reversing back to compressive residual stress at about 2.8mm into the workpiece.

2. With increase in cutting speed from 100m/min to 1000m/min, the predicted surface tensile residual stress decreases from 600 to 350 MPa.

3. The compressive residual stresses predicted at 4 mm depth into the workpiece were between the range -62 and -78 MPa

4. Predicted cutting forces in the Y direction were greater than feed force in the X-direction for all range of spindle speeds. Both forces increase with length of cut until they reach a steady state.

5. The maximum predicted cutting force and feed force were approximately 8300 and 4600 Newton respectively at 100m/min.

6. Predicted cutting power increases with increase in cutting speed. The cutting power increases from 8,500 Watts at 100m/min to 81,300 Watts at 1000m/min.

7. Simulation using finite element method can be a valuable and economic tool for predicting residual stresses and cutting forces.

8. The predicted tool temperature followed the same pattern as the main cutting force, and increases with increase in cutting speed. The maximum temperature at 100m/min and 1000m/min was predicted to be approximately 1350 degree and 1690 degree Centigrade respectively.

ACKNOWLEDGEMENT

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