Finite Element Modelling and Residual Stress Prediction in End Milling of Ti6Al4V alloy

Krishnakumar P\textsuperscript{1}, Sripathi J\textsuperscript{1}, Vijay P\textsuperscript{2}, Ramachandran K. I\textsuperscript{3}

\textsuperscript{1}Asst. Professor, Department of Mechanical Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India
\textsuperscript{2}B.Tech, Department of Mechanical Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India
\textsuperscript{3}Professor, Department of Mechanical Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India

*E-mail: p_kkumar@cb.amrita.edu

Abstract. Titanium and its alloys are materials that exhibit unique combination of mechanical and physical properties that enable their usage in various fields. In spite of having a lot of advantages, their usage is limited because they are difficult to machine due to their inherent properties of high specific heat capacity, reactivity with tool and low thermal conductivity thereby causing excessive tool wear. To facilitate the process of machining, it becomes necessary to find out and relieve the residual stress caused during machining. Since experiments cannot be performed for each instance, creation of an FE model is desirable. In this paper a finite element analysis (FEA) of the machining of Ti6Al4V for different cutting speeds is presented. A 3D finite element model is developed with the Titanium alloy (Ti6Al4V) as the workpiece and a four flute carbide tip end mill cutter as the tool to predict the residual stress developed within the titanium alloy after machining. The finite element model utilises the Johnson-Cook model to depict the plasticity and the damage criteria and implements the Arbitrary Lagrangian Eulerian (ALE) formulation to increase the accuracy of the model. The FE model has been developed and the findings are presented. The results indicate that residual stresses are maximum at the surface and decrease linearly along the depth and increase as the cutting speed and depth of cut are increased.

1. INTRODUCTION

Titanium alloys find their importance in various fields such as in aerospace, biomedical, automotive and marine applications. The reason behind their wide range of applications is attributed to their inherent properties such as high strength to weight ratio, their fracture resistance and high corrosion resistance [1]. In spite of possessing many advantages, their usage is hindered due to the resistance they offer in machining. This is said to be because of their low thermal conductivity [2]. Their low thermal conductivity [3] prevents the heat generated during machining to distribute within the workpiece thereby causing an increase in temperature on the tool tip which in turn causes an excessive tool wear [4].

Another important factor which inhibits the machining of the titanium alloy is the residual stresses that build up within the material after machining [5]. Residual stresses are stresses present within a material or a machined part after the machining process in the absence of any external forces or thermal gradients. These are the internal self-equilibrium stresses that are present in a component in the absence of any load. These residual stresses are of two types namely, compressive and tensile residual stresses. The residual stresses which are compressive in nature are beneficial since they enhance the fatigue life whereas the tensile residual stresses are detrimental in nature and are the ones that inhibit machining [6].

One of the best methods to accurately estimate the residual stresses developed within the material after machining is to develop a Finite Element model and simulate the process to get a better understanding of the processes like high speed milling which involves deformation with large strains, strain rates and temperature [7]. Numerical methods involving Finite Element Analysis (FEA) bridges the gap between the experiments and what actually happens within the process thereby providing a much deeper insight about the process. In order to improve tool life and productivity in machining of Titanium alloys, it is necessary to develop an appropriate FE model for various cutting regimes.
A 2D finite element model was developed by Jithin et al. [8] to study the variation of residual stress with the depth of cut. They found that residual stresses increased with depth of cut for a constant cutting speed and feed rate. Implementing Arbitrary Lagrangian-Eulerian (ALE) technique in an FE model has yielded accurate results in the simulation of material removal processes to Krishnakumar et al. [9] who studied the effect of residual stress in machining using ALE approach.

The validation the numerical model developed relies on various parameters such as the flow stress of the work material, the friction developed at the workpiece-tool interface, the fracture criterion of the workpiece and thermal parameters involved during machining. Thereby it requires that these parameters are chosen appropriately in order to obtain accurate results. Validation of the FE model can be done experimentally by measuring the residual stresses developed after machining of the titanium alloy by milling. Residual stress determination can be done by any of the conventional methods such as Center-hole drilling method [10], Incremental hole drilling method etc. [11] which are destructive methods.

Therefore, development of a finite element model would help in estimation of the residual stress developed during machining and thus help in facilitate the machining process. In this paper, the investigation of the residual stresses developed is done using the Johnson-Cook plasticity model [12] involving material constants as proposed by Lesuer [13]. The Johnson-Cook model has been implemented in the FE model to simulate the milling process of the Ti-6Al-4V alloy. In order to improve accuracy of the model, the Coulomb's law of friction and the Arbitrary Lagrangian-Eulerian (ALE) [14] technique is used in the model. The residual stress values are obtained by simulating the milling process and are presented in the form of plots for various cutting conditions. The FE model has to be developed incorporating Johnson-Cook model using the ALE formulation. The developed model is used to find the residual stress developed during the milling process.

2. FINITE ELEMENT MODELLING

2.1. Part modelling

The CAD model of the four flute end mill cutting tool was imported and the Titanium block workpiece was modelled in ABAQUS. The tool was defined as a rigid body while the workpiece was modelled as a deformable one. A reference point was created in the rigid body. The workpiece and the tool are shown in Figure 1.

2.2. Material Modelling

A number of empirical relations are available that predict the thermo-visco plastic behaviour of a material. One of the most commonly and widely used constitutive model is the Johnson-Cook (J-C) plasticity model. In the Johnson-Cook plasticity model [8] (shown in Eq. 2.1) the flow stress of a material depends on the equivalent plastic strain, strain rate and temperature.

\[
\sigma = \left[ A + B \varepsilon^n \right] \left[ 1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right] \left[ 1 - \left( \frac{T - T_0}{T_m - T_0} \right)^m \right]\
\]

where \( \sigma \) is the material flow stress, \( \varepsilon \) is the equivalent plastic strain, \( \dot{\varepsilon} \) is the strain rate (s\(^{-1}\)), \( \dot{\varepsilon}_0 \) is the reference strain rate (s\(^{-1}\)), \( T \) is the temperature of the workpiece (°C), \( T_m \) is the melting temperature of the workpiece and \( T_0 \) is the room temperature. Coefficient \( A \) (MPa) is the yield strength; \( B \) (MPa) the strain hardening modulus; \( C \) the strain rate sensitivity coefficient; \( n \) the hardening coefficient; \( m \) is the thermal softening coefficient. The three terms in the Johnson-Cook model are the elasto-plastic term, viscosity term and thermal softening term respectively.

The Johnson-Cook model parameters for Ti-6Al-4V as proposed by Lesuer [12] are specified in Table 1.

| A(MPa) | B(MPa) | C   | n     | m     | \( T_m \)(°C) |
|-------|-------|-----|-------|-------|-------------|
| 1098  | 1092  | 0.014 | 0.93  | 1.1   | 1604        |

2.3. Damage Criteria

Formation of chip and the removal of the same is an important aspect in the simulation of cutting process of a material. The chip formation occurs when the material subject to machining undergoes deformation, that is material fracture occurs. In order to model the material fracture in simulation, a damage criterion needs to be
employed. In this paper, the Johnson-Cook fracture criteria is implemented. The Johnson-Cook fracture model defines strain at fracture as:

\[
\varepsilon_{\text{failure}} = \left[ D_1 + D_2 \exp(D_3 \sigma^*) \right] \left[ 1 + D_4 \ln(\dot{\varepsilon}^*) \right] \left[ 1 + D_5 \left( \frac{T - T_0}{T_m - T_0} \right) \right]
\]  

(2.2)

where \( \sigma^* \) is the dimensionless pressure-stress ratio (stress triaxility parameter), \( \dot{\varepsilon}^* \) is the dimensionless plastic strain-rate and \( D_1, D_2, D_3, D_4 \) and \( D \) are material dependent fracture constants. The Johnson-Cook parameters for Ti-6Al-4V as proposed by Lesuer have been utilised for the finite element model and has been tabulated below in Table [2].

| Parameter | Value |
|-----------|-------|
| \( D_1 \) | -0.09 |
| \( D_2 \) | 0.270 |
| \( D_3 \) | 0.480 |
| \( D_4 \) | 0.014 |
| \( D_5 \) | 3.870 |
| \( T_{\text{melt}} \) (°C) | 1604 |

There exists a damage parameter which when exceeds 1 indicates that there is a material fracture. The damage parameter \( D \) is given by

\[
D = \sum \frac{\Delta \varepsilon^0}{\varepsilon_{\text{failure}}}
\]

(2.3)

The damage parameter \( D \) is expressed as the ratio of incremental effective plastic strain to the strain at fracture.

2.4. Contact Criteria

In the simulation of milling process, the tool-workpiece interaction is of much importance in order to obtain better results. The surfaces of the tool and workpiece form a contact pair providing master and slave surface wherein the tool forms the master surface and the workpiece forms the slave surface.

![Figure 1](image1.png)

Figure [1] FE Model developed, consisting of C3D8R elements

In the above FE model, Coulomb’s law of friction is used to model the contact criteria. This law is one of the most widely used criteria in metal cutting simulations.

2.5. Meshing

In the finite element simulation, the workpiece was meshed with C3D8R elements which is an 8 node linear brick elements, with reduced integration and hourglass control. The global element size was set as 0.5 to develop the mesh, which is shown in Figure [1]. The tool was meshed with tetrahedral type of mesh and the workpiece was meshed with hexagonal mesh. The meshing was done in such a manner that it is very fine up to a certain depth and the remaining part is meshed normally.

The distortion of nodal elements affects the numerical accuracy of the model. In order to avoid distortion, a remeshing procedure is employed. In this finite element model, an Arbitrary Lagrangian-Eulerian (ALE) technique is used which combines both Lagrangian as well as Eulerian formulations. In Lagrangian-based finite element formulations, the computational system is attached to the material. Eulerian-based finite element formulations are fixed in space. Arbitrary Lagrangian-Eulerian (ALE) combines the advantages of both the
methods and is widely used in simulations involving material removal processes. ALE overcomes the shortcomings of both Eulerian and Lagrangian formulations.

The boundary conditions were specified as per the physical conditions of machining. The bottom surface of the block was constrained in all 3 translational and rotational degrees of freedom were restricted. The tool was constrained in Y and Z directions and rotations about X and Z axis. The tool was given a velocity boundary condition equal to the feed rate in X direction and the tool rotation velocity in rotation about Y axis.

3. RESULTS AND DISCUSSIONS

The simulations were successfully completed for four different cutting conditions with varying depth of cuts while maintaining a constant feed rate of 200 mm/min and cutting speed of 120 m/min. The cutting conditions have been specified in Table [3].

| S. No. | Cutting Speed (m/min) | Depth of cut (mm) | Feed Rate (mm/min) |
|--------|-----------------------|-------------------|--------------------|
| 1      | 120                   | 0.030             |                    |
| 2      | 120                   | 0.045             |                    |
| 3      | 120                   | 0.060             |                    |
| 4      | 120                   | 0.075             |                    |
| 5      | 135                   | 0.030             |                    |
| 6      | 135                   | 0.045             |                    |
| 7      | 135                   | 0.060             |                    |
| 8      | 135                   | 0.075             |                    |
| 9      | 150                   | 0.030             |                    |
| 10     | 150                   | 0.045             |                    |
| 11     | 150                   | 0.060             |                    |
| 12     | 150                   | 0.075             |                    |

The residual stress plots were obtained by simulating the milling process on Titanium alloy in ABAQUS for the above mentioned conditions. The negative stresses are compressive stresses which are beneficial as they enhance fatigue life of the material whereas the positive stresses are tensile in nature and therefore need to be removed for further machining. A very large magnitude of the positive value of the stress is an indication of the fact that the machinability of the Titanium alloy is low.

The trend of the plots obtained from the simulations have a linear decreasing slope until a certain depth and then vary non-uniformly. The linear trend is observed until the mesh region is very fine and coarser mesh region attributes to the varying trends in the slope. This is because the material undergoes maximum stress near the machined layer or surface and hence the residual stress that remains after machining is maximum initially and decreases as we move along the depth of the material. The value of the residual stress obtained from the simulation was found to increase with increasing depth of cut. This proves that further machining of the Titanium alloy is inhibited as these residual stress increase in magnitude with increasing depth of cut.
Figure [3] Variation of Residual stress $\sigma_{11}$ along depth for a cutting speed of 120 m/min and depth of cut of 0.03 mm, 0.045 mm, 0.06 mm and 0.075 mm respectively, moving clockwise from top-left.

The plot shown in Figure [3] is a plot of residual stress in the X-direction ($\sigma_{11}$), along the depth of the Titanium alloy for a cutting speed of 120 m/min, subject to a depth of cut of 0.03mm, 0.045 mm, 0.06 mm and 0.075 mm. The plot for a depth of cut of 0.045 mm also follows a decreasing trend up to 3 mm but with a higher slope than that obtained at a depth of cut of 0.03mm. Similar trend is obtained for the depth of cuts of 0.06 mm and 0.075 mm with larger magnitude of residual stresses. This indicates that as depth of cut increases, the amount of residual stresses increase.

Figure [4] Variation of Residual stress $\sigma_{22}$ along depth for a cutting speed of 120 m/min and depth of cut of 0.03 mm, 0.045 mm, 0.06 mm and 0.075 mm respectively, moving clockwise from top-left.

The plot shown in Figure [4] depicts the variation of Residual stress in Y-direction ($\sigma_{22}$), along the depth of the Titanium block for various depth of cuts of 0.03 mm, 0.045 mm, 0.06 mm and 0.075mm. The plot at the top left obtained for a depth of cut of 0.03 mm has a decreasing slope with lower magnitude. As we move clockwise that is, as we increase the depth of cut, we observe that there is a change in slope and also in the magnitude of the residual stresses.
Figure [5] Variation of Residual stress $\sigma_{22}$ along depth for a cutting speed of 120 m/min and depth of cut of 0.03 mm, 0.045 mm, 0.06 mm and 0.075 mm respectively, moving clockwise from top-left.

The plot shown in Figure [5] shows the variation of Residual stress in the Z-direction ($\sigma_{33}$), along the depth of the material for different depth of cuts of 0.03 mm, 0.045 mm, 0.06 mm and 0.075 mm. The plots when observed clockwise, show a decreasing slope with each plot having a much steeper slope. Moreover, the magnitude of residual stress in each plot also increases thereby indicating that as depth of cut increases, the magnitude of residual stress also increases.

4. CONCLUSION

The end milling process of Ti-6Al-4V was simulated in the Finite Element software, ABAQUS. The Johnson-Cook plasticity model was implemented in the model which was responsible for the thermo-visco-plastic behaviour of the Titanium block. The selection of Johnson-Cook parameters also played an important role in the chip formation while machining. The simulation of the end milling process on Ti-6Al-4V provides a theoretical background on the impact of the residual stress developed within the material and its impact on machinability. This impact is provided in the form of plots which gives us an idea as to how much influence it has on the machining parameters.

The graphs presented in this paper indicate that the residual stress is at the surface is the maximum and has a positive value. The positive residual stress indicates that the further machining of the alloy is inhibited due to the residual stress accumulation. The residual stress decreases with depth, slowly transferring to negative residual stresses as depth increases. This is the general behavior of the Titanium alloy, wherein the residual stress keeps decreasing with depth.

After a depth of 3 mm, the region was coarse meshed as the residual stresses are expected to be less in magnitude which is confirmed by the plot obtained until a depth of 3 mm. The coarse meshed region shows very high changes in residual stress, which is caused due to the fact that the element size is very high that the stress gradients become large enough and the results become inaccurate.

This paper is presented with a view to investigate the residual stress development in Ti-6Al-4V numerically and provide a platform for the utilisation of these data to perform experiments and validate them and with that validation improve upon the feasibility of the usage of Ti-6Al-4V in various fields with improved machinability.

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