

3D Finite Element Simulation of the Milling Process of a Ti 6Al 4V Alloy

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Abstract: The milling process is one of the most common metal removal operations. It is widely used in a variety of manufacturing industries including the aerospace and automotive sectors. Intense international competition has focused the attention of manufacturers on automation as means to increase productivity and improve quality. Modeling and simulation of cutting processes have the potential for improving cutting tool designs and selecting optimum conditions, especially in advanced applications such as high-speed milling. The objective of this study was to develop a methodology for simulating the cutting process in end milling operation to predict tool, and workpiece stresses and temperatures using 3D finite element analysis with Abaqus/Explicit. Rectangular pieces of titanium Ti-6Al-4V were cut, the tool was an endmill coated with Aluminum Titanium Nitride with 4 cutting edges and 3/8" on a diameter of the tool. The milling was carried out over a length of 47 mm. The finite element model considers speed rate, feed and depth as input. High thermal gradients were found at the beginning of the cutting process regardless of cutting conditions. These temperatures increase wear of the cutting tool.

Keywords: Abaqus/Explicit, Super alloy, Titanium, Milling process, Cutting parameters.

1. Introduction

Ti-6Al-4V alloy offers a combination of high strength, light weight, formability and corrosion resistance which have made it a world standard in aerospace industry. Some applications of this alloy include aircraft turbine engine components, marine applications, medical devices, and sports equipment. Metal cutting of alloys involves very complex phenomena that are difficult to handle in an analytic fashion. Therefore numerical techniques will help to approximate the solution of the problem. One of the most widely numerical techniques used is the Finite Element Method (FEM).

Machining processes involve very complex phenomena altogether. Finite Element Modeling of Machining processes is a powerful tool to understand the mechanisms of chip formation, heat generation due to both plastic deformation and interfacial friction, and the mechanical integrity of the machined surface.

There are three different mechanical formulations that can be used. The Eulerian formulation, in which the mesh is not attached to the material, it is computationally efficient but needs to update

the free chip geometry. In the Lagrangian formulation, the mesh is attached to the material and requires updating of the mesh. Lagrangian formulation needs a chip separation criterion. There are several chip separation criteria such as displacement, strain energy density, stress, and effective plastic strain (Huang, 1996). An alternative method is to use Arbitrary Lagrangian Eulerian (ALE) formulation. In this case the mesh is not attached to the material and it can move to avoid distortion and update the free chip geometry. This work uses a similar procedure done by Özel et.al. (Özel, 2005), Gonzalez (Gonzalez, 2009), and Aspinwall (Aspinwall, 2002).

The workpiece material modeled was Ti-6Al-4V (125 x 47 x 22 mm). The Johnson Cook material model was employed to model the flow stress behavior. In the Johnson-Cook model, the flow stress is a function of the strain ϵ , strain hardening coefficient n , strain rate $\dot{\epsilon}$, reference strain rate $\dot{\epsilon}_0$, workpiece temperature T , room temperature T_∞ , melting temperature T_m , and strain rate sensitivity index m , as show in Equation 1:

$$\sigma_f = (A + B\epsilon^n) \left(1 + C \ln \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \right) \left(1 - \left(\frac{T - T_\infty}{T_m - T_\infty} \right)^m \right), \quad (1)$$

Where A, B, and C are constants taken from ElTogby, (ElTogby, 2005) for Ti-6Al-4V alloy. These constants are presented in Table 1:

Table 1.- Constants from Equation 1.

A (MPa)	B (MPa)	C	m	n
1090	1092	0.014	1.1	0.93

A dynamic, thermo-mechanical simulation was performed. To solve the problem, Abaqus/Explicit was used. The method has some important advantages for modeling machining processes:

1. It is computationally efficient for analyzing large models with dynamic response times.
2. It can be used to handle very complex contact conditions. Contact algorithms are robust and straightforward than their implicit counterparts.
3. It uses a consistent, large deformation theory models that undergo large deformation such as those encountered in machining processes.

The explicit scheme requires a time increment Δt which is less than a critical value Δt_{cr} to get a stable solution. Δt_{cr} is calculated automatically by Abaqus by Equation 2:

$$\Delta t_{cr} = \frac{L_e}{\sqrt{\frac{E}{\rho(1+\nu)}}}, \quad (2)$$

L_e is the effective length of the element, E is the modulus of elasticity, ρ is the material density, and ν is the Poisson's ratio. The analysis considers the heat generated by plastic straining of the material by using inelastic heat fraction option available in Abaqus. This method is typically used in the simulation of bulk metal forming or high-speed manufacturing processes involving large amounts of inelastic strain, where the heating of the material caused by its deformation is an important effect because of temperature dependence of the material properties. Since the Johnson-Cook plasticity model is motivated by high-strain-rate transient dynamic applications, temperature change in this model is generally computed by assuming adiabatic conditions (no heat transfer between elements). Heat is generated in an element by plastic work, and the resulting temperature rise is computed using the specific heat of the material, Equation 2, (Özel, 2005):

$$q_{pl} = \eta \sigma \dot{\epsilon}^{pl} = \rho c_p \dot{T} \quad (3)$$

In this investigation $\eta = 0.9$ is taking since it is commonly used in the literature (Habbitt, 2008). During the machining process, frictional contact occurs along the tool-chip interface, which affects chip formation, stress and strain distribution, and workpiece surface integrity (Shet, 2003). Interfacial friction is considered using Coulomb friction law assuming a friction coefficient of 0.3. Heat dissipation from friction conditions is also considered in this study, it is calculated by Equation 4:

$$q_f = f \tau \dot{\gamma} \quad (4)$$

τ is the frictional stress and $\dot{\gamma}$ is the slip rate, and f stands for the portion of the frictional heat that goes into the chip. The frictional heat is assumed to split evenly between the two surfaces, so that $f=0.5$.

2. Experimental procedure

Table 2 shows the experimental parameters taken into account for the cutting process, these are the depth of machining, the feed rate and speed. The machining was done in a Vertical Machining Center Bridgeport VMC 760, Figure 1, using rectangular pieces of titanium (Ti-6Al-4V) of size 125 x 47 x 22 mm. The tool was an endmill coated with Aluminum Titanium Nitride (AlTiN) with 4 cutting edges and 3/8" on a diameter of the tool, see Figure 2. The milling was carried out over a length of 47 mm.

Table 2. Machining parameters used for the test.

Condition	Units	Case A	Case B
Speed	m/min	70	90
Feed	mm/rev	0.11	0.15
Depth	mm	0.50	1.50



Figure 1. Vertical Machining Center Bridgeport VMC 760.



Figure 2. The material and the tool used in the test.

3. Model preparation

A full 3D thermo-mechanical problem was created. The following assumptions were made for the numerical analysis:

1. Thermal properties of both workpiece and tool are not considered as function of temperature.

2. Round edges of the tool is considered in order to avoid distortion of the mesh during the simulation.
3. Cooling conditions are not considered in the analysis.
4. The tool is modeled as a rigid material with a very high modulus of elasticity (800 GPa).

3.1 Chip formation

Chip separation from the workpiece and crack nucleation in the chip is possible using the Johnson-Cook failure model which allows the element deletion once the conditions for failure are met, see Equations 5 and 6. This model involves the strain at failure $\bar{\epsilon}_f^{pl}$, which was assumed to be dependent on a non-dimensional plastic strain rate $\dot{\bar{\epsilon}}^{pl}/\dot{\epsilon}_o$, a pressure-deviatoric stress ratio p/q (where p is the pressure stress and q the von Mises stress), and the temperature terms which were defined in Equation 1.

$$\bar{\epsilon}_f^{pl} = \left[d_1 + d_2 \exp\left(d_3 \frac{p}{q}\right) \right] \left[1 + d_4 \ln\left(\frac{\dot{\bar{\epsilon}}^{pl}}{\dot{\epsilon}_o}\right) \right] \left(1 + d_5 \left(\frac{T - T_\infty}{T_m - T_\infty} \right) \right) \quad (5)$$

The failure constants d_1 to d_5 are shown in Table 3 (Kay, 2003):

Table 3. Johnson-Cook failure constants for Ti-6Al-4V.

d_1	d_2	d_3	d_4	d_5
-0.09	0.27	0.48	0.014	3.87

Shear failure occurs in the model when the damage parameter w reaches unity, Equation 6:

$$w = \sum \left(\frac{\Delta \bar{\epsilon}^{pl}}{\bar{\epsilon}_f^{pl}} \right) = 1 \quad (6)$$

where $\Delta \bar{\epsilon}^{pl}$ is an increment of the equivalent plastic strain, and the summation is performed over all increments in the analysis.

When removing elements new contact surfaces are created. Contact between the workpiece and the tool was modeled using the general contact algorithm. During the analysis elements from the workpiece can fail (chip formation), which calls for the use of element-based surfaces that can adapt to the exposed surfaces of the current non-failed elements. The general contact algorithm supports element-based surfaces that evolve in this manner. To model removal of elements, a contact domain was included which includes surface faces that may become exposed during the

analysis, including faces that are originally in the interior of the element set, which requires the use of the INTERIOR face identifier on a data line of the *SURFACE option in the input file. Only the interior faces that are expected to participate in contact (chip elements) are included in the contact domain in this analysis to minimize the memory use:

```
*SURFACE, TYPE=ELEMENT, NAME=chip
chip_set_elements, INTERIOR
```

3.2 Meshing

In order to achieve accurate results for the machining simulation, the workpiece is partitioned with finer mesh near the contact zone with the cutting tool. Figure 3 shows the discretized model. The element type C3D8RT was selected with a total number of 85476 elements and 91037 nodes.

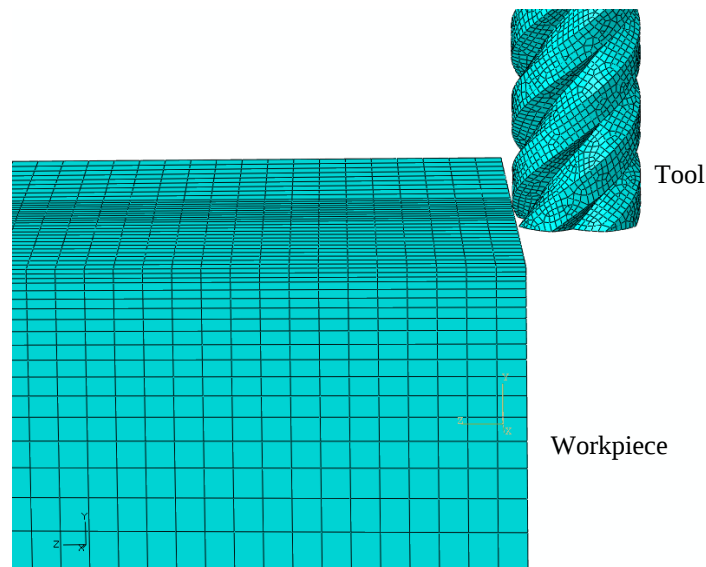


Figure 3. Discretized 3D model for the simulation of machining.

3.3 Boundary Conditions

Displacement boundary conditions are applied in order to prevent rigid body motion of the workpiece. The tool is constrained in x-z plane to allow only horizontal movement in x direction. Boundary conditions are shown in Figure 4. In Figure 4, v is velocity, and ω is the angular velocity. A temperature of 25°C is considered as an initial condition for the domain Ω .

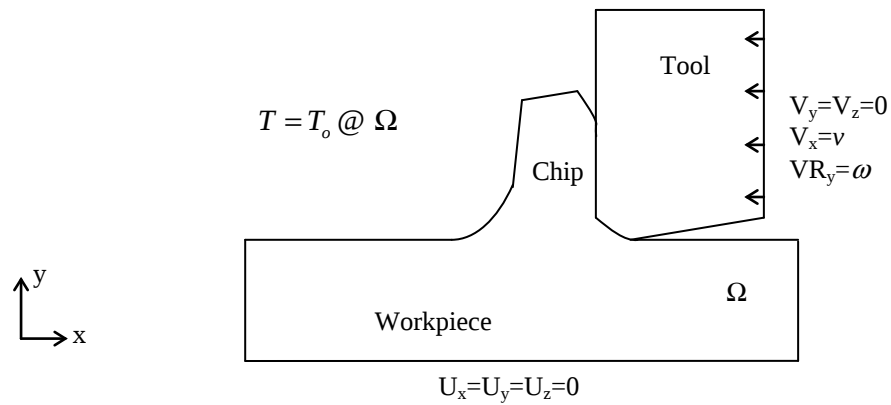


Figure 4. Boundary conditions for 3D model.

4. Results

Figure 5 shows the von Mises stress distribution in Pascals for case A. For this case $v=5.5$ mm/s and $\omega=2228$ rpm, see Figure 4. The magnitude of maximum stress was 1.37 GPa and was highly localized at the tool-workpiece contact region.

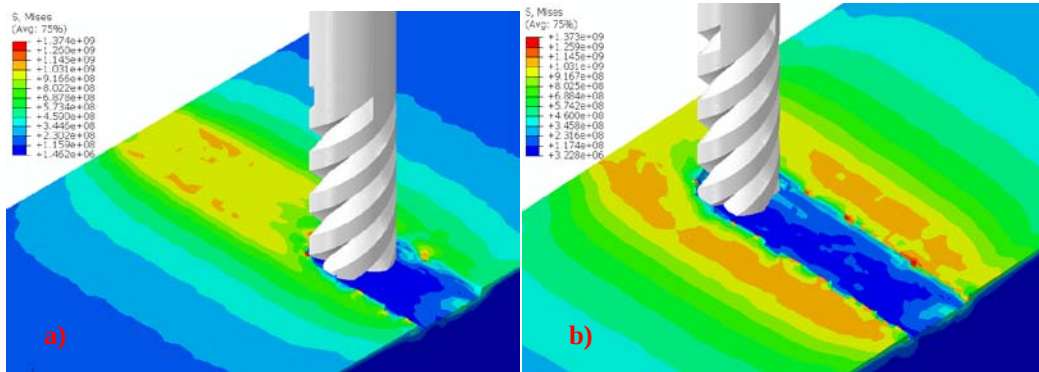


Figure 5. Von Mises stress distribution of 3D machining (Case B) at times 3.549 sec (a), and 6.845 sec. (b).

Figure 6 shows the temperature distribution in $^{\circ}\text{C}$ for case A:

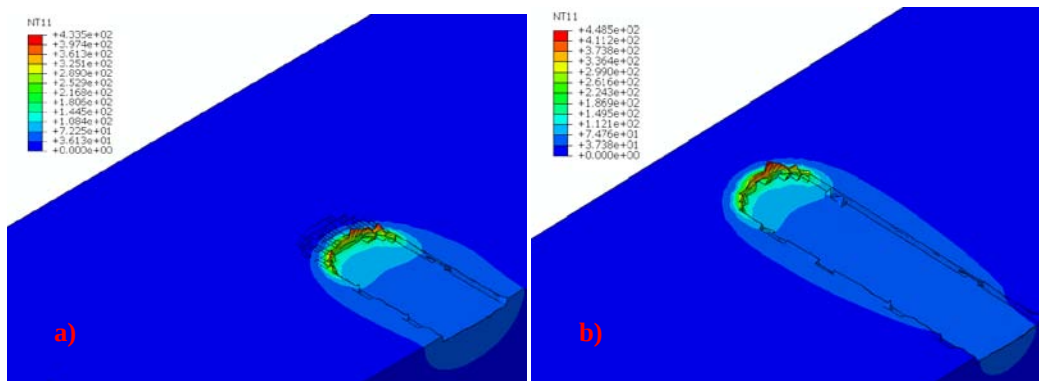


Figure 6. Temperature distribution of 3D machining (Case A) at times 3.549 sec (a), and 6.845 sec. (b).

Figure 7 shows the von Mises stress distribution in Pascals for case B. For this case $v=6.2$ mm/s and $\omega=2865$ rpm, see Figure 4. The magnitude of maximum stress was 1.28 GPa.

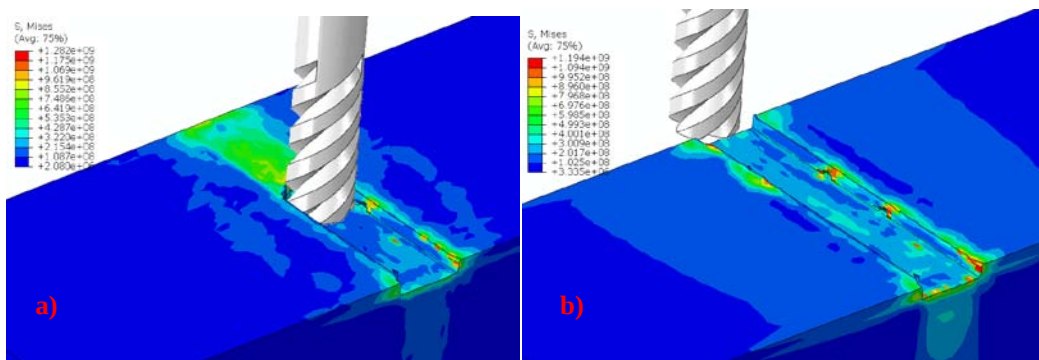


Figure 7. Von Mises stress distribution of 3D machining (Case B) at times 4.55 sec (a), and 9.1 sec. (b).

Figure 8 shows the temperature distribution in °C for case B:

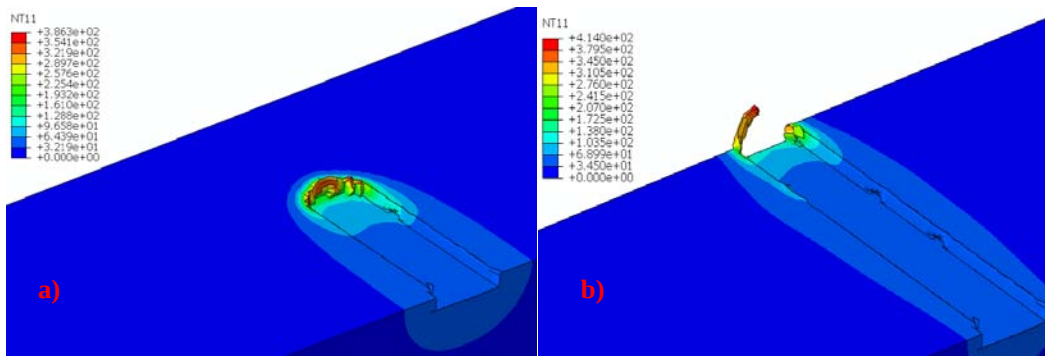


Figure 8. Temperature distribution of 3D machining (Case B) at times 4.55 sec (a), and 7.849 sec. (b).

Figures 6 and 8 show the temperature distributions (in °C) of workpiece and tool. It can be seen the high thermal gradients that are being formed due to friction and plastic deformation conditions. These thermal gradients can result in a rapid tool wear. Figure 9 shows a comparison between calculated and measured values of temperature for case B. It can be seen that a difference in almost 100 °C was found and this is due to the fact that the cutting tool was considered as a rigid body which needs to be able to "extract" heat from the machined surface and from the flowing material.

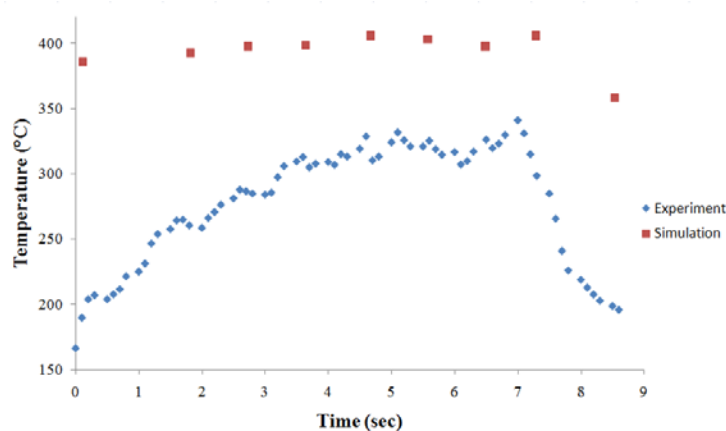


Figure 9. Temperature comparison (in °C) between experimental and calculated values for case B.

5. Conclusions and future work

This work has presented a methodology to study a machining process of Titanium alloy considering speed, feed, and depth of cut. Abaqus/Explicit was capable of modeling the milling process using Johnson-Cook shear strain failure criteria. This study will help to analyze more conditions affecting the machinability of Ti alloys and other materials such as Inconel, composites, or other expensive materials that are actually being used in industry more frequently. The benefits will be the reduction of experimental testings and economic waste. More work will be done to take into account more complex conditions such as residual stress calculations, cutting forces, cooling effects to enhance lubrication conditions, and tool wear to get more quantitative results.

6. References

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7. Acknowledgements

The authors acknowledge the financial support provided by the Consejo Nacional de Ciencia y Tecnología (CONACYT), México, Programa de Apoyo a la Investigación Científica y Tecnológica (PAICYT) – UANL and the facilities to carry out the experimental data recollection to the Facultad de Ingeniería Mecánica y Eléctrica (FIME)-UANL.