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Finite Element Modeling To Predict the Effect of Nose Radius on the Equivalent Strain (PEEQ) for Titanium Alloy (Ti-6Al-4V)

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Abstract**—**In present work, prediction the effect of nose radius, r_z (mm) on the equivalent strain (PEEQ) and surface finish during the machining of titanium alloy (Ti-6Al-4V) through orthogonal cutting process. The results were performed at several of the nose radiuses, r_z (mm) while the cutting speed, v_c (m/min), feed rate, f (mm/tooth) and depth of cut, d (mm) were remained constant. The equivalent plastic strain (PEEQ) was estimated by using finite element modeling (FEM) and applied through ABAQUS/EXPLICIT software. The simulation results led to conclude that the equivalent plastic strain (PEEQ) was increased and surface roughness (R_a) decreased when increasing nose radius, r_z (mm) during the machining of titanium alloy (Ti–6Al–4V) in dry cutting conditions.

Keywords**—**Finite element modeling (FEM), nose radius, plastic strain (PEEQ), titanium alloy (Ti-6Al-4V).

I. Introduction

TITANIUM alloy (Ti-6Al-4V) [1] is considered a hard and attractive material due to their unique high strength-density ratio that is maintained at elevated temperatures, and their exceptional corrosion resistance. The main application of titanium alloy (Ti-6Al-4V) is found in the aerospace industry that it is used in both airframes and engine components. There is non-aerospace application can take advantage mainly of their excellent strength properties and corrosion resistance [2, 3, 4]. These reasons led to become that titanium alloy (Ti-6Al-4V) is known as difficult to machine materials. Besides that, Kahles et al. [5] Claim that the surface of titanium alloy is easily damaged during machining operations, especially during milling and grinding. Then, Shahan and Taheri [6] were found that the report that the shear zones hardness depends on the alloy forming conditions and the widths of the adiabatic shear zones. Therefore, Xiaoping Yang and C. Richard Liu [1] were obtained that the strain in the chip is confined to narrow bands between the segments with very little deformation within these segments [3,7,8].

There is very limited work has been done in finite element simulation (FEM) of machining titanium alloy (Ti-6Al-4V) [1]. Therefore, a good finite element model would be very useful to optimize the machining process and led to reduce its cost, machining time saving, improved the quality and quantity.

The main goal of this research work predicts the effect of nose radius, r_z (mm) on the equivalent strain (PEEQ) and surface finish during the machining of titanium alloy (Ti-6Al-4V) in dry cutting conditions by using finite element modeling (FEM).

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II. Finite Element Modeling (FEM)

The finite element modeling (FEM) is considered a very good technique to obtain the machining parameters such as cutting force, stresses, temperature, and others analysis. Therefore, a typical finite element analysis on a software system requires the following information procedures:

1. Material and tool modeling by classifying (parts and properties).
2. Contact and failure laws analysis.
3. Meshing elements and boundary conditions.

A. Materials and Tools Modeling

A fully thermo-mechanically coupled implicit is considered. The materials and tools modeling are carried out by using finite element modeling (FEM). The work-piece material dimension of 50 mm x 100 mm with machining parameters; cutting speed, v_c (m/min), cutting depth, d (mm), and feed rates, f (mm/tooth) are shown in Table I.

TABLE I
Machining Parameter Modeling

Cutting Parameters				
Angles		Cutting speed, v_c (m/min)	Depth, d (mm)	Feed rate, f (mm/tooth)
Rake, γ (deg)	Clearance, α (deg)			
4	19	100	1	0.2

The cutting tool geometry is modeled with the supposition mechanically rigid. Selected rake angle and clearance angle according to the design of cutting tool geometry as shown in Table I. Hence, it can be seen the cutting tool geometry as shown in Fig. 1.

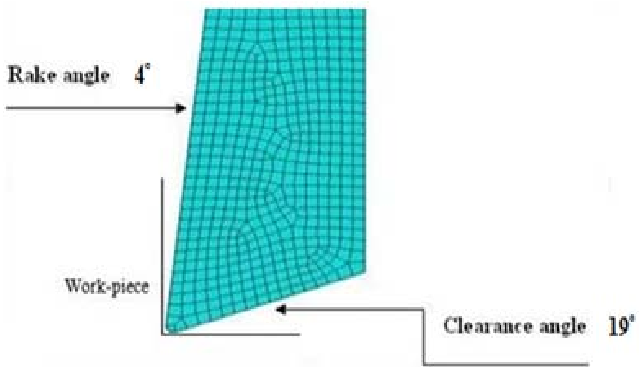

Fig. 1 Tool geometry

B. Contact and Failure Laws Analysis

The machining parameters have been estimated through finite element modeling (FEM). In addition, the failure parameters d_1 to d_5 are obtained from R. Lesuer [9]. Where: d_1 = -0.09, d_2 = 0.25, d_3 = -0.5, d_4 = 0.014, and d_5 = 3.87. In this study, titanium alloy (Ti-6Al-4V) is modeled with the Johnson–Cook plasticity model of Eq. 1. Besides that, the material failure strain ε_f is detailed in Eq. 2, as below:

$$\sigma = \left(A + B\,\varepsilon_p^n\right)\left(1 + C\,ln(\dot{\varepsilon}/\dot{\varepsilon}_o)\right)\left(1 - \left(\frac{T-T_r}{T_m-T_r}\right)^m\right) \quad (1)$$

$$\varepsilon_f = \left(d_1 + d_2\, e^{d_3(\sigma_p/\sigma_e)}\right)\left(1 + d_4\, \ln(\dot{\varepsilon}^p/\dot{\varepsilon}_o)\right)\left(1 + d_5\left(\frac{T-T_r}{T_m-T_r}\right)\right) \quad (2)$$

where: σ is flow stress, ε^p and ε are strain and strain rate, ε_o is the reference strain rate (*1/s*) and *n*, *m*, *A*, *B* and *C* are constant parameters for Johnson - Cook material model as shown in Table II. ($\varepsilon^p/\varepsilon_o$) as a function of non-dimensional plastic strain, a dimensionless pressure stress ratio (σ_p/σ_e), where: σ_p is the pressure stress and σ_e is the stress (Von-Mises), work piece temperature (T), room temperature (T_r), and melting temperature (T_m) [10].

TABLE II
CONSTANT PARAMETERS FOR JOHNSON-COOK MATERIAL MODEL OF TITANIUM ALLOY (TI-6AL-4V) [11]

Cutting constant	Values
A (MPa)	987.8
B (MPa)	761.5
n	0.41433
m	1.516
C	0.01516
Reference strain rate (1/*s*)	2000
Young's modulus (GPa)	113.8
Poisson's Ratio	0.342
Melting Temp.°*C*	1605
Density (kg/m^3)	4428

C. Meshing Elements and Boundary Conditions

From the Fig. 1 and Fig. 2, the mesh generator starts by creating elements along the boundary of the work-piece and cutting tool. The meshing elements and boundary conditions used at the contact surface between the cutting tool edge and work-piece of titanium alloy (Ti-6Al-4V). The total number of elements is used with approximately about 5882 and the number of nodes is 6103. The work-piece material was divided two parts upper with minimum element size of 0.1 µm and lower size of 0.3 µm. This is because the mesh elements in the cutting zone should be very small to get accurate results. On the other hand, the lower part is important to reduce the time during simulation process. In addition, the tool was meshed with the minimum element size of 0.1 µm.

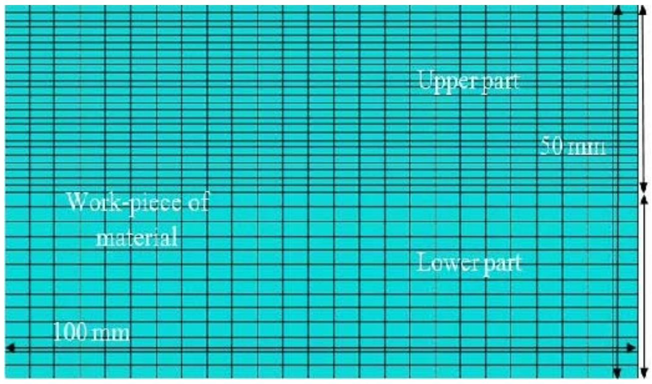

Fig. 2 Meshing elements for work-piece of titanium alloy (Ti-6Al-4V)

III. RESULTS AND DISCUSSION

The current study can estimate the equivalent plastic strain (PEEQ) at several nose radiuses, r_z (mm) while the cutting speed, v_c (m/min), feed rate, *f* (mm/tooth) and depth of cut, *d* (mm) were held constant. Besides that, their values were estimated by using finite element modeling (FEM) as shown in Table III. The simulation result of the equivalent plastic strain at integration points (PEEQ) was increased and the surface finish decreased when increasing the nose radius as shown in Fig. 3, Fig. 4 and Fig. 5.

TABLE III
MACHINING PROCESS PERFORMED AT SEVERAL NOSE RADIUSES

Simulation numbers	Nose Radiuses (r_z) mm	Cutting Parameters		
		Cutting speed, v_c (m/min)	Feed rate, *f* (mm/tooth)	Depth, *d* (mm)
S1	0.8	100	0.2	1
S2	1.2			
S3	1.6			

The first simulation (S1), it could be seen the maximum equivalent plastic strain at integration points (PEEQ) was 1.365 at nose radius, r_z = 0.8 mm. The increasing was done in the primary shear zone deformation with a large dispersal of chip formation in front the cutting tool edge. Therefore, the result shows that surface finish was a flimsy as shown in Fig. 3.

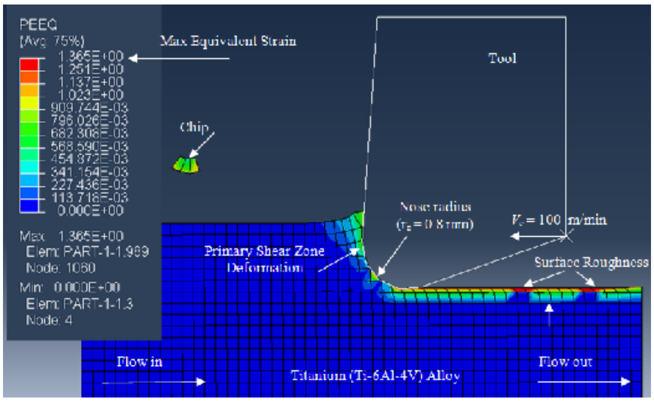

Fig. 3 The equivalent plastic strain (PEEQ) and surface finish estimated using FEM at nose radius, r_z = 0.8 mm

The second simulation (S2), it shows the maximum equivalent plastic strain at integration points (PEEQ) was 1.414 at nose radius, r_z = 1.2 mm. Then, the primary shear zone deformation was found less than it's created at nose radius, r_z = 0.8 mm. In this respect, the surface finish was improved during this cutting condition as shown in Fig. 4.

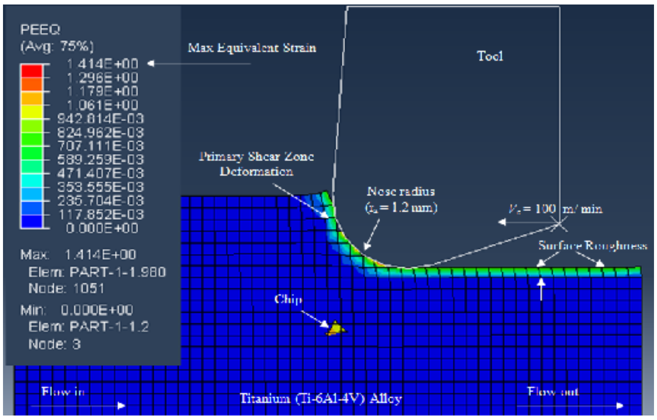

Fig. 4 The equivalent plastic strain (PEEQ) and surface finish estimated using FEM at nose radius, r_z = 1.2 mm

The third simulation (S3), it can be seen the maximum equivalent plastic strain at integration points (PEEQ) was 1.483 at nose radius, r_z = 1.6 mm. Furthermore, the primary shear zone deformation and surface finish was improved in this cutting condition more than the other simulation tests were done before as shown in Fig. 5.

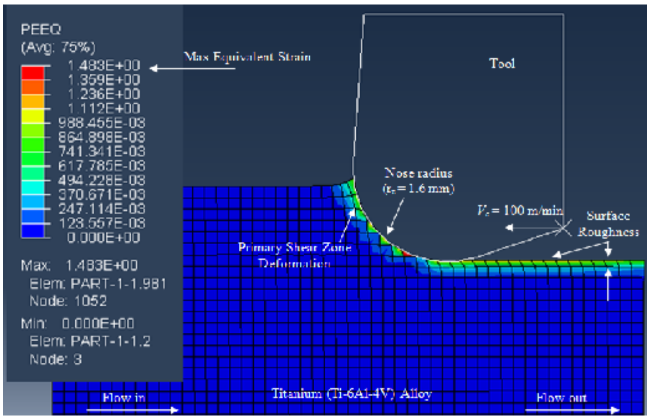

Fig. 5 The equivalent plastic strain (PEEQ) and surface finish estimated using FEM at nose radius, r_z = 1.6 mm.

IV. Conclusion

From the obtained results, the conclusion can be drawn as follows:

- Finite element modeling (FEM) is considered a good platform for all researchers are focusing to contribute in reduce the costs of manufacturing in terms of prolongs the cutting tool life and machining time saving due to improve the productivity. Therefore, the prediction of machining parameters was carried out by using finite element modeling (FEM).
- The equivalent plastic strain at integration points (PEEQ) was increased when increasing the nose radius, r_z (mm) during the cutting simulation process of titanium alloy (Ti-6Al-4V).
- The nose radius, r_z (mm) is affected on the cutting parameters during the machining process of titanium alloy (Ti-6Al-4V) and it is considered one of the most important parameters to control a surface finish by reducing a surface roughness (R_a).

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