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The Effect of Nose Radius on Cutting Force and Temperature during Machining Titanium Alloy (Ti-6Al-4V)

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***Abstract*—**This paper presents a study the effect of nose radius (R_z-mm) on cutting force components and temperatures during the machining simulation in an orthogonal cutting process for titanium alloy (Ti-6Al-4V). The cutting process was performed at various nose radiuses (R_z-mm) while the depth of cut (d-mm), feed rate (f-mm/tooth) and cutting speed (v_c-m/ min) were remained constant. The main cutting force (F_c), feed cutting force (F_t) and temperatures were estimated by using finite element modeling (FEM) through ABAQUS/EXPLICIT software and the simulation was developed the two-dimension via an orthogonal cutting process during machining titanium alloy (Ti-6Al-4V). The results led to the conclusion that the nose radius (R_z-mm) has affected directly on the cutting force components. However, temperature gave no indication or has no significant relation with nose radius during machining titanium alloy (Ti-6Al-4V). Hence, any increase or decrease in the nose radius (R_z-mm) during machining operation led to effect on the cutting forces and thus it will be effective on surface finish, quality, and quantity of products.

***Keywords*—**Finite element modeling (FEM), nose radius, cutting force, temperature, titanium alloy (Ti-6Al-4V).

I. Introduction

TITANIUM alloy [1] is an attractive material due to their unique high strength-weight ratio that is maintained at their exceptional corrosion resistance and elevated temperatures. The main application of titanium alloy is found in the aerospace industry that it is used in both engine components and airframes. There is non-aerospace application can take advantage mainly of corrosion resistant and their excellent strength properties [2]-[4]. These reasons led to become that titanium alloy (Ti-6Al-4V) is known as difficult machining materials.

Researchers are focusing to use a wide range of tools and techniques to ensure that the designs they are created it saves. Probably, sometimes accidents could happen while they work in the laboratories or factories. Industries need to know whether a product failed or how many percentage need to success it. Nevertheless, they have to ensure that the product works well under a wide range of conditions and try to avoid from failure due to any cause. In this regard, finite element modeling (FEM) could help to avoid the failure and improve the success. Therefore, it is considered one of the most important factors affecting the cutting process is tool geometry (nose radius). Hence, discuss the effects of nose radius based on prediction method by using FEM [11].

FEM is a very important technique for machining application analysis because it can produce very accurate and significant results. In general modeling the plastic material flow, contains two basic approaches to assigning elements [5]. Firstly, fixing the elements in space and allowing the material to flow through them (Eulerian technique) and secondly, dividing the material into elements that move with the flow (Lagrangian technique). Therefore, the Johnson-Cook constitutive model of titanium alloy (Ti-6Al-4V) had been established earlier and developed.

The cutting process of titanium alloy (Ti-6Al-4V) was simulated by using an orthogonal cutting of finite element model. However, in this simulation, the Johnson-Cook model considered the adiabatic effect is more accurately [6].

The main purpose of this research paper is a study the effect of nose radius (R_z - mm) on the cutting force components and temperature during the machining simulation process for titanium alloy (Ti-6Al-4V) through an orthogonal cutting process by using finite element modeling (FEM).

II. Finite Element Modeling (FEM)

Finite element modeling (FEM) is considered one of the important techniques of numerical simulation methods. It can estimate accurate results such as cutting forces, temperature, and surface roughness or other desired unknown parameters in the finite element model. Therefore, a commercial finite-element ABAQUS/EXPLICIT software system requires the following information procedures:

1. Work-piece material and tool modeling
2. Contact and failure laws analysis
3. Meshing elements, assembly parts and boundary conditions

A. Work-piece Material and Tool Modeling

The finite element modeling was developed (2D) of an orthogonal cutting process for titanium alloy (Ti-6Al-4V) and it was considered fully thermo-mechanically coupled implicit [7]. The work-piece material of titanium alloy (Ti-6Al-4V) is designed by using a dimension of 60 mm x 100 mm with machining parameters; cutting depth (d – mm), feed rate (f - mm/tooth), cutting speed (v_c – m/min). The tool geometry is

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designed by selecting rake angle and clearance angle as shown in Table I. In addition, tool geometry is designed with the assumption mechanically rigid in this simulation process.

TABLE I
CUTTING PARAMETERS MODELING

Angle		Cutting Parameters		
Rake, γ (deg)	Clearance, α (deg)	Depth d (mm)	Cutting speed, v_c (m/min)	Feed rate, f (mm/tooth)
0	11	1	100	0.2

B. Contact and Failure Laws Analysis

The simulation results have been estimated by using FEM. In addition, the failure parameters d_1 to d_5 are acquired from [8]. Where: d_1= -0.09, d_2 = 0.25, d_3 = -0.5, d_4 = 0.014, and d_5 = 3.87. In this respect, the work-piece of titanium alloy (Ti-6Al-4V) is modeled with the Johnson–Cook plasticity model refers to (1). Besides that, the failure strain (εf) is detailed as refer to (2) as:

$$\sigma = (A+B\,\varepsilon_p{}^n)\,(1+C\,ln\,(\varepsilon/\varepsilon_0)\,(1-((T-T_r)/(T_m-T_r))^m) \quad (1)$$

$$\varepsilon f = (d_1 + d_2\, e^{d3(\sigma_p/\sigma_e)})(1+d_4 \ln(\varepsilon^p/\varepsilon_0))(1+d_5((T-T_r)/(T_m-T_r))^m) \quad (2)$$

where: σ is flow stress, ε_p and ε are the 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. ($\varepsilon^p/\varepsilon_o$) is 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), room temperature (T_r), and melting temperature (T_m) [9].

TABLE II
CONSTANT PARAMETERS FOR THE J-C MODEL AND PHYSICAL PARAMETERS OF TITANIUM ALLOY (TI-6AL-4V) [10], [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
Density, ρ (kg/m^3)	4428
Young's modulus (GPA)	113.8
Poisson's ratio	0.342
Specific heat, *Cp* (J/kg °C)	670
Thermal conductivity, λ (W/m°C)	6.6
Expansion Coeff., (μm/m/°C)	9
T room (°C)	25
T melting (°C)	1605
Inelastic heat fraction (β)	0.9

C. Meshing Elements, Assembly Parts and Boundary Conditions

From Fig. 1, the mesh generator starts by creating elements along the boundary conditions of the work-piece material and cutting tool. The meshing elements and assembly parts between work-piece material and tool geometry were created at the contact surface between the cutting tool edge and the work-piece material of titanium alloy (Ti-6Al-4V) as shown in Fig. 1. The total number of elements used is approximately about 11286 and the number of nodes used is 11512 for work-piece of titanium alloy (Ti-6Al-4V) via using an orthogonal cutting process.

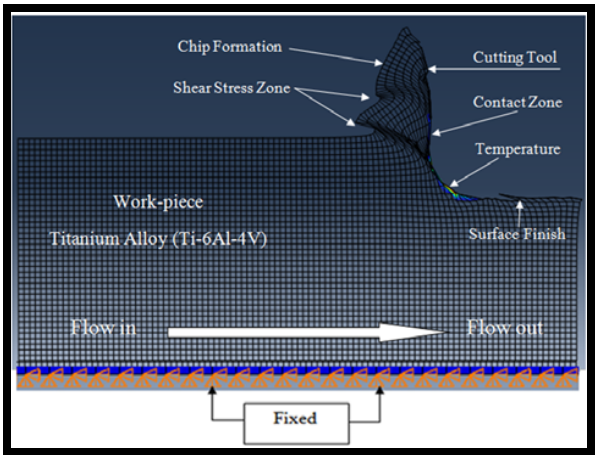

Fig. 1 Meshing elements and boundary conditions in the cutting zone

III. RESULTS ANALYSIS

The finite element modeling (FEM) is estimated the cutting forces and temperatures as well. The cutting force components such as the main cutting force (F_c) and feed cutting force (F_t) were estimated at two points while several nose radiuses (R_z-mm). Test results are estimated from FEM while several nose radiuses as shown in Table III. On the other hand, temperatures are given no indication or has no significant relation with nose radius during machining titanium alloy (Ti-6Al-4V) as shown in Fig. 2.

TABLE III
TEST RESULTS ESTIMATED FROM FEM WHILE VARIOUS NOSE RADIUSES IN DRY CUTTING CONDITIONS

Machining Simulation Tests	Nose Radius R_z-mm	Cutting parameters were remained constant (d, f, v_c)			
		Main Cutting Force (F_c) N		Feed Cutting Force (F_t) N	
		Point 1	Point 2	Point 1	Point 2
T1	0.8	1136	903	585	259
T2	1.2	1132	1453	529	525
T3	1.6	1290	1151	641	258

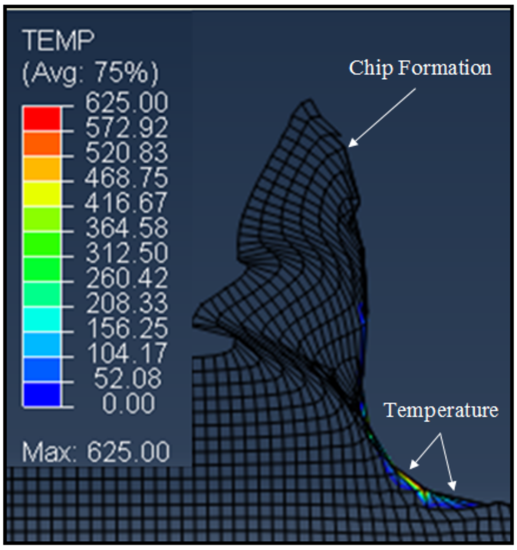

Fig. 2 Temperature estimates at various nose radiuses using FEM

IV. Discussion

The nose radius (R_z-mm) has affected on the cutting forces (F_c, F_t) according to the machining simulation tests estimated at two different points of the work- piece material for titanium alloy (Ti-6Al-4V). The final results were obtained from (T1) and (T3) that the values of main cutting force (F_c) were decreased from point 1 to point 2. This behavior indicates that a strength influence of nose radius (R_z-mm) at the main cutting force during the cutting process as shown in Fig. 3. However, test (T2) is observed that the main cutting force (F_c) was increased depends on the value of nose radius (R_z-mm) as shown in Fig. 3. On the other hand, (T1) and (T3) were found that the feed cutting force (F_t) was deeply decreased from point 1 to point 2 that is described their values of a fall sharply as shown in Fig. 4. This is because the main cutting force was decreased already at (T1) and (T3) that it means under these cutting conditions the nose radius effects by decreasing cutting forces. Therefore, it can be observed when decreasing cutting forces as well as surface roughness was decreased and thus it will be improved surface finish of the work-piece material. Although, test (T2) is observed that the feed cutting force (F_t) was also decreased, but a little bit from points 1 to point 2 that is related to increasing in the main cutting force as shown in Fig. 4. Cutting processes have shown a significant relationship between main cutting force (F_c) and feed cutting force (F_t) during machining titanium alloy (Ti-6Al-4V) according to machining simulation tests. Therefore, any increase or decrease in the nose radius (R_z-mm) during the machining process led to effect on the machining parameters of titanium alloy (Ti-6Al-4V) and thus surface finish. Hence, this prediction will be affected positively on the machining process and surface roughness value because it improves the quality and quantity of products.

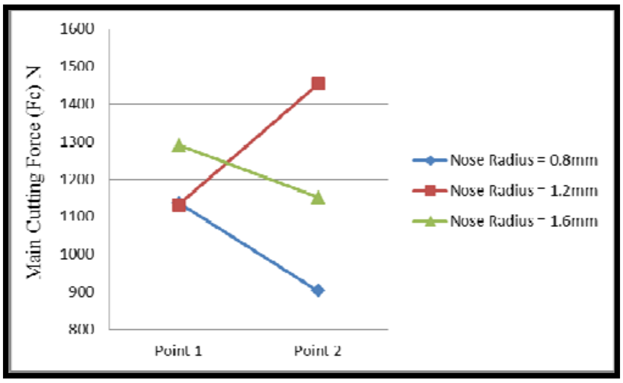

Fig. 3 Main cutting force (F_c) estimated at various nose radiuses

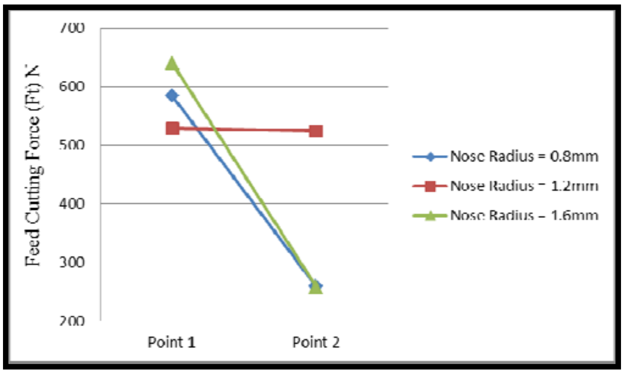

Fig. 4 Feed cutting force (F_t) estimated at various nose radiuses

V. Conclusions

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

1. Nose radius (R_z) is considered one of the most important factors affecting on the cutting process, so predict it by using FEM, which is led to improve the quality and quantity of products.
2. FEM is a very important technique for machining application analysis because it can produce very accurate and significant results.
3. FEM can contribute in reducing the cost of manufacturing in terms of prolongs the cutting tool life and machining time saving to improve the productivity.
4. Any increase or decrease in the nose radius (R_z) led to affect directly on the machining parameters and thus surface finish as well.
5. Temperatures are given no indication or has no significant relation with nose radius during machining titanium alloy (Ti-6Al-4V).
6. Increase in the nose radius is led to decrease in the cutting forces as well as surface roughness and thus it will be improved surface finish.

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