Simulation Study on Cutting Force and Cutting Temperature in Turning of Titanium Alloy

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Abstract. The objective of this paper is to study the cutting force and cutting temperature in turning of titanium alloy. The simulation of cutting force and cutting temperature by finite element simulation software ABAQUS is conducted. The orthogonal experiment is designed. The influence of various factors on cutting force and cutting temperature is obtained. A prediction model of cutting temperature and cutting force is obtained by performing multiple linear regression analysis on the data obtained from orthogonal experiments.

1. Introduction
Titanium alloys represent a significant metal portion of the aircraft structural and engine components due to their excellent properties such as high strength-to-weight ratio, toughness, superb corrosion resistance, bio-compatibility and high fatigue strength[1]. ASTM grade 5 (Ti6Al4V) is the most common Ti-alloy used and accounts for more than 50% of all Ti-alloy used[2]. Unfortunately, titanium alloys are generally classified as difficult-to-machine materials because of certain inherent properties[3]. Low thermal conductivity causes heat dissipation difficulty within the machining zone which creates high thermal gradients leading to rapid tool wear. Lower elastic modulus causes excessive workpiece deflection and moves away from the cutting tool, which corresponds to badly machined surface integrity. The great deflection of thin-walled structures results in tool vibration, chatter, and poor surface finish. Due to the chemical affinity between the workpiece and tool in high temperature, chemical wear occurs in the cutting tool. All these problems are related to the severe high cutting force and temperature-induced during the cutting process.

Significant researches on machining titanium alloys have been performed to enhance the tool life and improve the machined surface integrity. The machined surface stress distribution has a direct impact on the fatigue strength of the machined part. Stress, temperature, and vibration in the machining zone are the three main factors that enhance the cutting tool damage[4]. During the machining process, the high temperatures are generated by strength and hardness of the enhancement of the material which accelerates tool wear[5]. Titanium alloys retain their strength even at high temperatures, up to about 550 °C[6]. Titanium is highly reactive with the tool materials at high temperatures. For getting higher productivity, cutting speeds are required higher. The tool life is very short and results in a poor surface finish at high cutting speed. For instance, machining at speeds over 90 m/min had a tool life less than 10 min[7]. By optimizing the process parameters, abundant studies have been conducted to obtain better cutting conditions[8-10]. The tool geometry combination may significantly reduce cutting force and temperature which will improve the machinability of titanium alloys. Using advanced lubrication and cooling methods such as minimum quantity lubrication (MQL)
and cryogenic cooling techniques has some benefits to improve the machining process with environmental friendliness.

In this research, a numerical analysis of cylindrical external turning on Ti6Al4V alloy is presented. A Johnson-Cook constitutive equation was implemented as a flow stress model and adapted to the Ti6Al4V alloy. Through the 2D finite element simulation procedure, the cutting forces and temperatures were gotten with several sets of cutting conditions such as different combinations of cutting parameters and tool geometries. Orthogonal experiments have been designed for optimizing the cutting and tool parameters with five factors and four levels. Finally, a prediction model has been obtained by performing multiple linear regression procedure.

2. Finite Element Simulation

In this paper, the numerical simulation procedure is aimed at testing the feasibility of a material constitutive model for the Ti6Al4V when implemented in a 2D FE model of a turning operation under dry cutting conditions. 2D FE model for orthogonal cutting has been simulated by utilizing the commercial FEA code ABAQUS/Explicit™. Workpiece material of Ti6Al4 was modeled as plastic. The cutting tool was modeled as a rigid body. Figure 1 shows the system of relative motion between workpiece and tool.

![Figure 1. Schematic diagram of two-dimensional orthogonal cutting](image1)

To avoid serious distortion of the mesh in simulation, an improved Lagrange mesh generation method is adopted. The mesh generation is not uniform, but relatively fine near the cutting part for simplifying the simulation procedure. The FE simulation model is shown in Figure 2. The number of elements used in simulations was about 9000 (8000 for upper 40 layers and 1000 for lower 5 layers) for workpiece. The density deviation method was used for tool meshing. In the simulations, X-axis represented the cutting direction and Y-axis represented the feed direction. Boundary conditions of the workpiece were determined with respect to various cutting speeds.

![Figure 2. The finite element simulation model](image2)
The material and tool properties are given in Table 1[11]. The room temperature $T_0$ was set equal to 20°C for dry cooling. The fracture criterion for chip separation based on equivalent plastic strain was used in this paper.

Table 1. Properties of workpiece and tool

|          | Elastic modulus (GPa) | Poisson ratio | Thermal conductivity (W/m°C) | Specific heat (J/kg°C) |
|----------|-----------------------|---------------|-------------------------------|------------------------|
| Workpiece (Ti6Al4V) | 113                   | 0.342         | 7                             | 546                    |
| Tool (carbide)    | 800                   | 0.2           | 46                            | 203                    |

Johnson-Cook (J-C) material model was used to determine the strain rate sensitivity in the simulations. Table 2 shows different coefficient values suggested for the J-C Model of Ti6Al4V alloy from previous studies [12].

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

Table 2. Johnson-Cook material model parameters for Ti6Al4V

| $A$ (MPa) | $B$ (MPa) | $C$ | $n$       | $m$ |
|-----------|-----------|-----|-----------|-----|
| 1098      | 1092      | 0.93| 0.014     | 1.1 |

The cutting forces and temperatures are partially generated by the frictions between the chip and rake face. The sliding zone and bonding zone describe the two different contact states. The shear stress at each point in the bond zone is substantially the same, and the friction in the slide zone decreases along the rake angle. Due to the complexity of friction configuration, the penalty function method was adopted to deal with the sliding friction in this paper.

3. Orthogonal experiments design

The study aims to investigate experimentally effects of cutting parameters and cutting tool geometry on the cutting main force and temperature in the turning of Ti-6Al-4V alloy. From single factor simulation experiment, one can find the changing tendency affected by a single cutting parameter or tool geometry. The cutting process is a complicated procedure and the cutting parameters and tool geometry have strong dependent relation acting on the cutting forces and temperature. Among these factors, the effect degrees for cutting force and temperature were checked by designing several orthogonal experiments.

The design of experiments has a major effect on the number of experiments needed. Therefore, it is essential to have a proper design of experiments. A factorial design was selected in this work so that all the interactions between the independent variables can be investigated. In this study the five parameters namely rake angle, relief angle, tool nose radius, cutting speed and cutting depth of the cutting tool were selected for the experimentation. The five selected factors with four levels are shown in Table 3.

Table 3. Cutting parameters and tool geometry of titanium alloy turning

| Level | Rake angle ($^\circ$) | Relief angle ($^\circ$) | Tool nose radius (mm) | Cutting speed (m/min) | Cutting depth (mm) |
|-------|-----------------------|-------------------------|-----------------------|-----------------------|-------------------|
| 1     | 0                     | 6                       | 0.1                   | 30                    | 0.1               |
| 2     | 5                     | 8                       | 0.2                   | 50                    | 0.125             |
| 3     | 10                    | 10                      | 0.3                   | 60                    | 0.15              |
| 4     | 15                    | 12                      | 0.4                   | 80                    | 0.175             |
The Taguchi method is executed for finding the optimum number of experiments with the combinations of parameters. An L16(4^5) orthogonal array was formed based on the five factors-four level design. A total of sixteen experiments have been completed using uncoated carbide tools for machining at different cutting conditions selected through L16 orthogonal array. After sixteen runs of simulation, the cutting forces and temperatures have been gotten. The factor effect degrees are determined by equation (2) where \( R_j \) (\( j = 1, \ldots, 5 \) corresponding 5 factors) is the average (\( n = 4 \) for 4 levels) range of \( K_{ij} \). \( K_{ij} \) denotes the summation of \( n \) sets of simulated cutting force (temperature) with the \( i \)th level fixed for the \( j \)th factor.

\[
R_j = \frac{(k_{ij})_{\text{max}} - (k_{ij})_{\text{min}}}{n}
\]  

(2)

The average range \( R_j \) have been derived from sixteen runs of simulation experiment shown in Figure 3 where (a) indicates the cutting force range change and (b) for the cutting temperature one. By observing the range curve, one can find that the effect degree for cutting force is depth of cut \( a_p > \) rake angle \( \gamma_0 > \) tool nose radius \( r > \) cutting speed \( V_c > \) relief angle \( \alpha_0 \), and the effect degree for cutting temperature is cutting speed \( V_c > \) depth of cut \( a_p > \) rake angle \( \gamma_0 > \) relief angle \( \alpha_0 > \) tool nose radius \( r \).

\[0.0724 0.1175 0.1512 0.0961 0.8964\]  

Figure 3. The average range \( R_j \) of five factors for cutting force (a) and temperature (b)

4. Prediction model establishment

In the section, linear regression analysis methods were used to analyse the data derived from previous experiments to find out mathematical relation between cutting force (temperature) and cutting/tool geometric parameters. Regression equations were finally given for all experimental trials to represent the relation between dependent and independent variables. The model of predicted cutting force, \( F_R \) can be expressed as equation (3).

\[F_R = C \gamma_0^{b1} a_0^{b2} r^{b3} V_c^{b4} a_p^{b5}\]  

(3)

where \( C, b_1, b_2, b_3, b_4, \) and \( b_5 \) are model parameters. By logarithmic transformation equation (3) can be written as

\[Y = c + b_1 R + b_2 A_0 + b_3 R + b_4 V + b_5 A_p\]  

(4)

where \( Y = \ln F_R, R = \ln \gamma_0, A_0 = \ln a_0, R = \ln r, V = \ln V_c, \) and \( A_p = \ln a_p \). Residual analysis was executed and the abnormal experimental data has been eliminated. The regression model was solved on MATLAB\textsuperscript{TM}. Figure 4 is an example of residual analysis for deleting the abnormality of trials results where the dashed line indicates the abnormal data. After the multivariable linear regression procedure, the prediction model between cutting force and cutting parameters was built as equation (5) with solved unknown equation coefficients.

\[F_R = 1436.12 \gamma_0^{-0.0724} a_0^{0.1175} r^{0.1512} V_c^{0.0961} a_p^{0.8964}\]  

(5)
By utilizing a similar procedure, the prediction model between cutting temperature and cutting parameters has been solved as shown in equation (6).

\[ T = 635.49 \gamma_0^{0.0575} \alpha_0^{0.0171} r^{-0.0355} V_c^{0.0474} a_p^{0.1677} \] (6)

For examining the accuracy of the prediction models, three trials have been randomly selected. The predicted and simulated values of cutting force are represented in Figure 5.

5. Conclusion
This paper presents an FE model of turning on Ti6Al4V under dry cooling conditions. Johnson-Cook model was implemented and coupled with a hybrid bounding – sliding friction condition in the cutting contact zone. The influence on cutting force and temperature has been checked by designing orthogonal experiments using the Taguchi method with five cutting factors with four levels. The effect degree for cutting force is \( a_0 > \gamma_0 > r > V_c > \alpha_0 \), and the effect degree for cutting temperature is \( V_c > a_p > \gamma_0 > \alpha_0 > r \). Predictive models for determining the cutting forces and temperature were developed in the turning operation of Ti6Al4V.

Acknowledgments
The authors gratefully acknowledge the support by the Educational Department of Liaoning Province (grant number JDL2016014) and Department of Science & Technology of Liaoning Province (grant number 20170540146).

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