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Cutting Force and Tool Life Models in End Milling Titanium Alloy Ti-4Al-4V with Thermally-Assisted Machining

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Abstract: Titanium and its alloys are known as difficult-to-cut material due to some circumstances, such as high chemical reactivity, low thermal conductivity, low modulus of elasticity, and high strength at elevated temperature. Furthermore, higher cutting force and lower tool life in machining of these alloys are very common. An approach to reduce the cutting force and increase the tool life is to employ thermally-assisted machining. The working piece surface was heated up until a certain temperature just before cutting. This paper presents an approach to establish mathematical models for cutting force and tool life in end milling of titanium alloy Ti–6Al–4V using PCD inserts under thermally-assisted machining using high frequency induction heating. Response surface methodology (RSM) was employed in developing the cutting force and tool life models in relation to primary cutting parameters such as cutting speed, feed, and preheating temperature. Design-expert software was applied to establish the first-order and the second-order model and develop the contours. The adequacy of the predictive model was verified using analysis of variance (ANOVA) at 95% confidence level.

Keywords: Titanium alloy Ti-6Al-4V, end-milling, thermally-assisted machining

1 INTRODUCTION

Machining fluids provide many benefits to ensure that metal parts can be cut at lower cost. The advantages of such fluids have been established, such as friction reduction, cooling effect, corrosion protection, welding protection from the tool to the workpiece and the washing away of metal chips. But the usages of cutting fluid have undergone intense regulatory scrutiny during the last 20 years. For instance, the United Auto Workers petitioned the Occupational Safety and Health Administration (OSHA) to reduce the permissible exposure limit for metalworking fluids from 5.0 mg/m^3 to 0.5 mg/m^3. In response, OSHA established the Metalworking Fluid Standards Advisory Committee (MWFSAC) in 1997 to develop standards or guidelines related to metalworking fluids. In its final report in 1999, MWFSAC recommended that the exposure limit be 0.5 mg/m^3 and that medical surveillance, exposure monitoring, system management, workplace monitoring and employee training are necessary to monitor worker exposure to metalworking fluids [1].

Hence, to reduce the usage of cutting fluids, many metal cutting researchers have been proposing thermally-assisted machining or preheated machining as an option. It is believed that thermally–assisted machining process which includes preheating of work-piece prior to cutting is gaining interest as it results in reduced shear strength creating a condition conducive to metal cutting [2]. Maity and Swain [3] employed plasma assisted heating in turning of high manganese steel using carbide tool. They concluded that the effect of increased workpiece temperature would have a very significant effect on tool life. Ozler *et al* [4] integrated plasma gas heating in turning of austenitic manganese steel and noticed that tool life would increase with increase in heating temperatures. It is also concluded that the decrease in the strength of the workpiece is induced by the influence of heat most of which is transferred to the chip-tool interface. Turnad *et al* [5] used induction heating for end milling of titanium alloy Ti-6Al-4V. The results lead to conclusions that workpiece preheating significantly increases the tool life of uncoated WC-Co carbide inserts in end-milling of Ti-6Al-4V. An increase in tool life by 325% was achieved while employing preheating at 650°C compared to the experiment at room temperature.

In order to develop an adequate relationship between the cutting force during cutting and the cutting parameters (such as cutting speed, depth of cut, feed, etc), a large number of tests are needed, requiring a separate set of tests for each combinations of cutting parameters. This increases the total number of tests and as a result the experimentation cost also

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increases. As a group of mathematical and statistical techniques, response surface methodology (RSM) is useful for modeling the relationship between the input parameters and output responses. RSM could save cost and time by reducing number of experiments required.

In assessing machinability, some researchers have tried to employ response surface methodology to design their experimentations, and to establish the models. Turnad *et al* [6] utilized response surface methodology to develop tool life models for end-milling of titanium alloy Ti-6Al-4V using uncoated tungsten carbide inserts. It was found that the cutting speed was the main factors on the tool life, followed by the feed and axial depth of cut. Increase many of these three cutting variables leads to reduction of tool life. Kaye *et al* [7] used response surface methodology in predicting tool flank wear using spindle speed change. A tool life model which predicted tool flank wear was developed. Alauddin *et al* [8] applied response surface methodology to optimize the surface finish in end milling of Inconel 718. Choudhury and el-Baradie [9] found that response surface methodology coupled with the factorial design of experiments were useful techniques for tool life testing. Relative smaller number of designed experiments is required to generate much useful information that could be used to develop the predicting equation for tool life. Mansour *et al* [10] developed a surface roughness model for end milling of a semi - free cutting carbon casehardened steel. They investigated a first-order equation covering the speed range 30–35 m/min and a second-order generation equation covering the speed range 24–38 m/min. They suggested that an increase in either the feed or the axial depth of cut increases the surface roughness, whilst an increase in the cutting speed decreases the surface roughness. Sharif *et al* [11] used factorial design coupled with response surface methodology in developing the surface roughness model in relation to the primary machining variables such as cutting speed, feed, and radial rake angle.

The main objective of the current work is to establish the cutting force and tool life models of PCD inserts in end milling titanium alloy Ti-6Al-4V under thermally-assisted machining. Cutting force and tool life models were established based on cutting parameters, i.e. cutting speed, feed and preheating temperature. Design-expert Version 6.0.8 package was used to analyze the data and to develop the models. The adequacy of the model was tested at 95% confidence level.

2 EXPERIMENTAL DETAILS

The design of experiments has an effect on the number of experiments required. Therefore, it is essential to have a well-design experiment so that the number of experiments required can be minimized. A small central composite design consisting of 14 experiments was used in the experiments. This design provides five levels for each independent variable, as shown in Table 1. The most preferred classes of response surface designs are orthogonal first-order design and the central composite second-order design. A small central composite design, an orthogonal first-order design (with three factors) consisting of 8 experiments has been used to develop the first order model. These 8 tests consist of 4 corner points located at the vertices of the cube and a centre point repeated four times as illustrated in Figure 1. As the first-order model is only acceptable over a narrow range of variables, the experiments were extended to develop the second-order model. A second-order model is developed by adding six augmented points to the factorial design. Depending on the capacity of the cutting tool, an augmented length of $\pm\sqrt{2}$ was chosen. The augment points consist of three levels for each of the independent variables denoted by $-\sqrt{2}$, 0, $+\sqrt{2}$. The coded values of the variables shown in Table 1 were obtained from the following transforming equations:

$$\begin{aligned} x_1 &= \frac{\ln V - \ln 127}{\ln 175 - \ln 127} \\ x_2 &= \frac{\ln f_z - \ln 0.088}{\ln 1.28 - \ln 0.088} \\ x_3 &= \frac{\ln \theta - \ln 450}{\ln 580 - \ln 450} \end{aligned} \qquad (1)$$

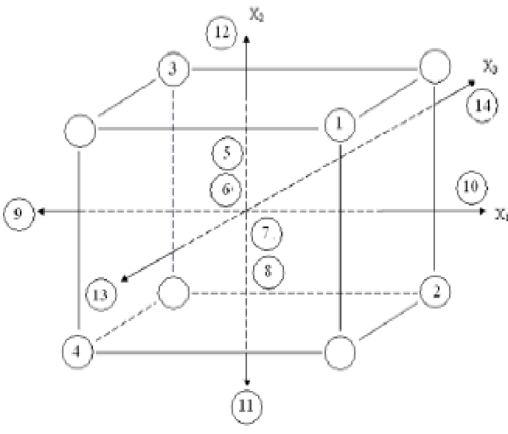

Figure 1- Small central composite design

Table 1- Level of independent variables and coding identification

Levels	Lowest	Low	Centre	High	Highest
Coding	$-\sqrt{2}$	-1	0	+1	$+\sqrt{2}$
X_1, Cutting speed, V	80.5	92	127	175	200
X_2, Feed, f_z	0.05	0.06	0.088	0.128	0.15
X_3, Preheat. temp.	315	350	450	580	650

Note: V (m/min), f_z (mm/tooth), Preheat temp (^0C)

3 EXPERIMENTAL WORK

End milling tests were conducted on Vertical Machining Centre (VMC ZPS, Model: MLR 542). Titanium alloy Ti-6Al-4V bar was used as the work-piece. Machining was performed with a 20 mm diameter endmill tool holder fitted with one insert. Polycrystalline diamond (PCD) inserts were used in the experiments. All of the experiments were run with preheating. High frequency induction heating was utilized to run the preheated machining. Cutting force and torque measurements were conducted using the Kistler rotating cutting force dynamometer. The experimental set up for the machining is shown in Figure 2.

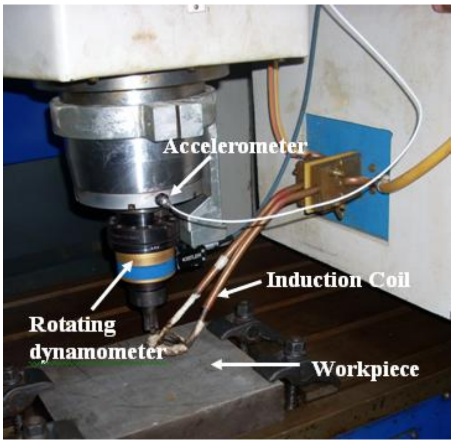

Figure 2: The experimental setup

Depending on the cutting conditions and wear rate, machining was stopped at various interval of cutting length from 100-200 mm to record the wear of the inserts. Flank wear has been considered as the criteria for tool failure and the wear was measured under a Hisomet II Toolmaker's microscope. Tool wear experiments were stopped when an average flank wear achieved exceeded 0.3 mm.

4 RESULTS AND DISCUSSION

4. 1 Cutting Force

Two components of the cutting force were measured directly, i.e. *Cutting Torque* in z-axis, M_z (N.m) and *Thrust Force*, acting along z-axis, F_z (N). The Torque about z-axis M_z was then converted to *Tangential Force (F_t)* by dividing it with the radius of the tool holder as follows:

$$F_t = \frac{M_z}{Radius\,of\;tool\,holder} \tag{2}$$

The Resultant Force (F_R) was calculated from the *Tangential Force (F_t)* and the *Thrust Force (F_z)* using the equation:

$$F_R = \sqrt{(F_t^2 + F_z^2} \tag{3}$$

The data on cutting force during end milling are presented in Table 2.

Table 2-Cutting force results during cutting

No.	Coding of level			Resultant Force (N)
	X_1	X_2	X_3	
1	-1	-1	-1	200.2
2	1	1	-1	337.8
3	1	-1	1	212.9
4	-1	1	1	341.0
5	0	0	0	288.1
6	0	0	0	278.6
7	0	0	0	298.3
8	0	0	0	294.0
9	-1.414	0	0	360.5
10	1.4142	0	0	266.6
11	0	-1.41	0	268.5
12	0	1.414	0	496.0
13	0	0	-1.414	300.4
14	0	0	1.414	265.6

The first-order model for cutting force which is obtained from experimental data in Table 2 is as follows:

$$\hat{y} = 5.73 - 0.047\,x_1 + 0.21x_2 - 0.0057\,x_3 \tag{4}$$

By substituting Eq. 1 into Eq. 4, the transformed equation of cutting force model is as follows:

$$F = 2767 \quad V^{-0.146}\; f_z^{\,0.56}\; \theta^{-0.023} \tag{5}$$

The ANOVA test for first-order model as shown in Table 3 reveals that cutting speed and preheating temperature are insignificant factors affecting the resultant cutting force, whereas the feed influences the cutting force significantly. Eq. 5 also indicates that an increase in cutting speed and preheating temperature decreases the cutting force, whereas an increase in feed increases the cutting force.

Tabel 3-Analysis of variance for cutting force first-order model

Source	SS	MS	F Value	Prob > F	
Model	0.37	0.12	4.45	0.03	Signi-ficant
x_1	0.02	0.01	0.63	0.4	
x_2	0.35	0.35	12.7	0.006	
x_3	0.003	0.0002	0.009	0.9	
Residual	0.24	0.02			
Lack of Fit	0.24	0.04	16.2	0.02	Not signi-ficant
Pure Error	0.007	0.002			
Cor Total	0.6				

4.2. Tool Life

The data of tool life based on flank wear is presented in Table 4. The ANOVA test for first-order model is presented in Table 5. The test reveals that all the cutting parameters significantly affect the tool life. An increase in cutting speed and feed leads to decrease the the tool life, whereas an increase in preheating temperature increases the tool life. The lack of fit was also found to be insignificant, indicating that the model could be used for tool life prediction.

Table 4-Tool life based on flank wear

No.	Coding of level			Tool life (min)
	X_1	X_2	X_3	
1	-1	-1	-1	33.4
2	1	1	-1	3.5
3	1	-1	1	36.7
4	-1	1	1	13.36
5	0	0	0	17.1
6	0	0	0	23
7	0	0	0	21
8	0	0	0	18.1
9	-1.414	0	0	34.5
10	1.4142	0	0	11.3
11	0	-1.41	0	20.05
12	0	1.414	0	4.8
13	0	0	-1.414	11.35
14	0	0	1.414	30.23

The first-order model of the tool life under preheated conditions obtained from experimental data in Table 4 is as follows:

$$\hat{y} = 2.79 - 0.35x_1 - 0.66x_2 + 0.35x_3 \qquad (6)$$

Eq. 6 is then transformed using Eq. 1 to provide the tool life (min) as a function of the cutting speed, V (m/min), feed, f_z (mm/tooth) and preheating temperature, θ (^{0}C) as follows:

$$T = 0.01\ V^{-1.09}\ f_z^{-1.76}\ \theta^{1.37} \qquad (7)$$

This equation is valid for end milling under thermally-assisted machining within the cutting speed, feed and preheating temperature ranges of: $80.5 \le V \le 200$ m/min, $0.5 \le d \le 2.03$ mm, and $315 \le \theta \le 650$ ^{0}C, respectively.

Tabel 5-Analysis of variance for cutting force first-order model

Source	SS	MS	F Value	Prob > F	
Model	5.48	1.82	16.8	0.0005	Signi ficant
x_1	0.99	0.9	9.19	0.0142	
x_2	3.49	3.49	32.2	0.0003	
x_3	0.99	0.99	9.16	0.0143	
Residual	0.97	0.10			
Lack of Fit	0.91	0.15	8.18	0.0564	Not signi ficant
Pure Error	0.05	0.01			
Cor Total	6.51				

From the development of cutting force and tool life models, it is always interesting to develop a new relationship of those models. The relationship model of cutting force and tool life from Eq. 5 and Eq. 7 can be re-written as:

$$\left(\frac{F}{T}\right) = 276700\ V^{0.9}\ f^{2.3}\ \theta^{-1.3} \qquad (8)$$

The equation informs that the force-tool life ratio is significantly affected by the feed and preheating temperature, whereas the cutting speed shows insignificant effects.

5 CONCLUSION

The following conclusions have been drawn on the work:

1. Response surface methodology have been successfully proved as a method for developing models for tool life and cutting force during thermally-assisted machining of titanium alloys using PCD inserts.
2. It is found that feed significantly affect the cutting force. It is also found that preheating temperature would not give significant effects in reducing cutting force in end milling of titanium alloys. However, an increase in preheating temperature decreases the cutting force.
3. Tool life equation informs that feed and preheating temperature significantly affects the tool life. Furthermore, an increase in preheating temperature increases the tool life significantly. It can be concluded that thermally-assisted machining should be an option to increase the tool life of cutting tool.

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