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TOOL LIFE PREDICTION BY RESPONSE SURFACE METHODOLOGY FOR END MILLING TITANIUM ALLOY Ti–6Al–4V USING UNCOATED CARBIDE INSERTS

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ABSTRACT

This paper presents an approach to establish models for tool life in end milling of titanium alloy Ti–6Al–4V using uncoated carbide inserts under dry conditions. Small central composite design (CCD) was employed in developing the tool life model in relation to primary cutting parameters such as cutting speed, axial depth of cut and feed. Flank wear has been considered as the criteria for tool failure and the wear was measured under a Hisomet II Toolmaker's microscope. Further testing was stopped and an insert rejected when an average flank wear greater than 0.30 mm was achieved. Design-expert version 6.0.8 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: Tool life, Response surface, Uncoated WC-Co, Ti – 6Al – 4V

1. INTRODUCTION

The performance of a cutting tool is normally assessed in terms of its life. Wear criteria are usually used in assessing tool life. Mostly, flank wear is considered, since it largely affects the stability of the cutting wedge and consequently the dimensional tolerance of the machined work surface [1]. Titanium alloys are generally difficult to machine at cutting speed at of over 30 m/min with high speed steel (HSS) tools, and over 60 m/min with cemented tungsten carbide (WC) tools, resulting in a very low productivity [2]. With the evolution of a number of new cutting tool materials, advanced tool materials such as cubic boron nitride (CBN) and polycrystalline diamond (PCD) have been developed. These tools have the good potential for use in high speed milling. However, polycrystalline diamond is currently very expensive. In addition, it is highly reactive with titanium alloys at higher temperatures, hence, its performance in machining of titanium alloys should be assessed.

In order to develop an adequate relationship between the tool life 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 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. Kaye *et al* [3] used response surface methodology in predicting tool flank wear using spindle speed change. A unique model has been developed which predicts tool flank wear, based on the spindle speed change, provided the initial flank wear at the beginning of the normal cutting stage is known. Alauddin *et al* [4] applied response surface methodology to optimize the surface finish in end milling of Inconel 718. Fuh and Wang proposed a predicted milling force model for end milling operation. They found that the proposed predicted milling force had a good correlation with experimental values [5]. Choudhury and el-Baradie 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 [6]. Choudhury and El-Baradie also used response surface methodology for assessing machinability of Inconel 718. They found that the dual response contours of tool life and surface roughness are very useful in assessing the maximum attainable tool life for the same surface finish [7]. Mansour *et al* 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 [8]. Oktem *et al* used response surface methodology with a developed genetic algorithm (GA) in the optimization of cutting conditions for surface roughness [9]. S. Sharif *et al* 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 [10].

The main objective of the current work was to establish the tool life models of uncoated tungsten carbide inserts in end milling titanium alloy Ti-6Al-4V under dry conditions. Tool life models were established based on cutting speed, axial depth of cut and feed. Small central composite design (CCD) was used to design the experimentations. 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. MATHEMATICAL MODEL

Tool life mathematical model for end milling in terms of the cutting parameters can be expressed as:

$$T = CV^{k} a^{m} f_{z}^{l} \qquad (1)$$

Where, *T* is the predicted tool life (minutes), *V* is the cutting speed (m/min), *a* is the axial depth of cut (mm) and f_z is the feed per tooth (mm/tooth), and *C, k, m*, and *l* are model parameters to be estimated using the experimental results. To determine the constants and exponents, this mathematical model can be linearized by employing a logarithmic transformation, and (1) can be expressed as:

$$\ln T = \ln C + k \ln V + m \ln a + l \ln f \qquad (2)$$

The linear model of (2) is:

$$y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \qquad (3)$$

Where, y is the true response of surface roughness on a logarithmic scale $x_0 = 1$ (dummy variable), x_1, x_2, x_3 are logarithmic transformations of speed, axial depth cut, and feed respectively, while $\beta_0, \beta_1, \beta_2,$ and β_3 are the parameters to be estimated. Equation (3) can be expressed as:

$$\hat{y}_1 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \qquad (4)$$

where, $\hat{y}$ is the estimated response and y the measured tool life on a logarithmic scale, ε the experimental error and the *b* values are estimates of the β parameters.

The second-order model can be extended from the first-order model's equation as:

$$\hat{y}_2 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \qquad (5)$$

Where $\hat{y}_2$ is the estimated responses based on the second order models. Analysis of variance (ANOVA) is used to verify and validate the model.

3. EXPERIMENT DETAILS

3.1 Experimental Design and Conditions

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 central composite 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. 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 Fig. 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 for use in (4) and (5) were obtained from the following transforming equations:

$$x_1 = \frac{\ln V - \ln 70.1}{\ln 126 - \ln 70.1} \qquad x_3 = \frac{\ln f_z - \ln 0.088}{\ln 0.128 - \ln 0.088}$$
$$x_2 = \frac{\ln a - \ln 1}{\ln 1.65 - \ln 1} \qquad (6)$$

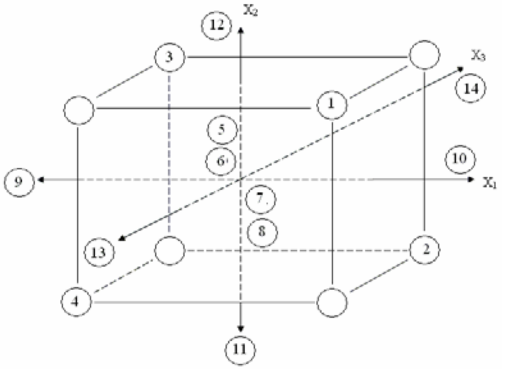

Fig 1: Small central composite design

Table 1: Level of the independent variables and coding identifications

Levels	Lowest	Low	Centre	High	Highest
Coding	$-\sqrt{2}$	-1	0	+1	$+\sqrt{2}$
x_1, cutting speed (m/min)	30.59	39	70.1	126	160.6
x_2, axial depth of cut, (mm)	0.5	0.61	1	1.65	2.03
x_3, feed, (mm/tooth)	0.05	0.06	0.088	0.128	0.15

3.2 Experimental Works

End milling tests were conducted on Vertical Machining Centre (VMC ZPS, Model: MLR 542 with full immersion cutting under dry condition. Titanium alloy Ti–6Al–4V bar was used as the work-piece. Machining was performed with a 20 mm diameter end-mill tool holder (R390-020B20-11M) fitted with one insert. Uncoated carbide inserts (R390-11T3 08E-NL-H13A) were used in the experiments. All of the experiments were run under dry conditions and each test was started with a new cutting edge. Depending on the cutting conditions and wear rate, machining was stopped at various interval of cutting length from 20 mm to 60 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. Further testing was stopped and an insert rejected when an average flank wear greater than 0.30 mm was recorded. The experimental design in coding of level and actual values are presented in Table 2.

Table 2: Experimental design in coding of level and actual values

No	Coding of Level			*V*	*a*	f_z
	X_1	X_2	X_3			
1	-1	-1	-1	39	0.61	0.060
2	1	1	-1	126	1.65	0.060
3	1	-1	1	126	0.61	0.128
4	-1	1	1	39	1.65	0.128
5	0	0	0	70.1	1	0.088
6	0	0	0	70.1	1	0.088
7	0	0	0	70.1	1	0.088
8	0	0	0	70.1	1	0.088
9	-1.41	0	0	30.59	1	0.088
10	1.41	0	0	159.7	1	0.088
11	0	-1.41	0	70.1	0.5	0.088
12	0	1.41	0	70.1	2.03	0.088
13	0	0	-1.41	70.1	1	0.050
14	0	0	1.41	70.1	1	0.150

4. RESULTS AND DISCUSSION

4.1 Tool Life Analysis

The tool life (T), metal removal (MR), and metal removal per tool life (MR/T) data are given at Table 3. Fig. 2 shows the flank wear versus cutting time of different cutting conditions. Run 1 with low level (-1) for all cutting parameters, will give a highest tool life (59.1) with 26.87 cm^3 for metal removal value. Hence, this run gives 0.45cm^3/min for metal removal per tool life. Run 10 has 5.2 min in tool life with 23.09 cm^3 for metal removal value. So, this run has 4.48cm^3/min for metal removal per tool life value. We can affirm that trial number 10 has the best productivity as observed in the experimentations.

Table 3: Experimental results

No	Coding of Level			MR (cm^3)	T (min)	MR/T (cm^3/min)
	X_1	X_2	X_3			
1	-1	-1	-1	26.87	59.1	0.45
2	1	1	-1	34.64	8.7	3.97
3	1	-1	1	24.41	7.8	3.13
4	-1	1	1	93.54	35.7	2.62
5	0	0	0	33.61	17.1	1.96
6	0	0	0	30.18	15.4	1.96
7	0	0	0	34.01	17.3	1.96
8	0	0	0	35.76	18.2	1.96
9	-1.41	0	0	37.77	44.1	0.86
10	1.41	0	0	23.09	5.2	4.48
11	0	-1.41	0	16.67	17.1	0.97
12	0	1.41	0	72.50	18.2	3.99
13	0	0	-1.41	31.51	28.2	1.12
14	0	0	1.41	35.70	10.7	3.35

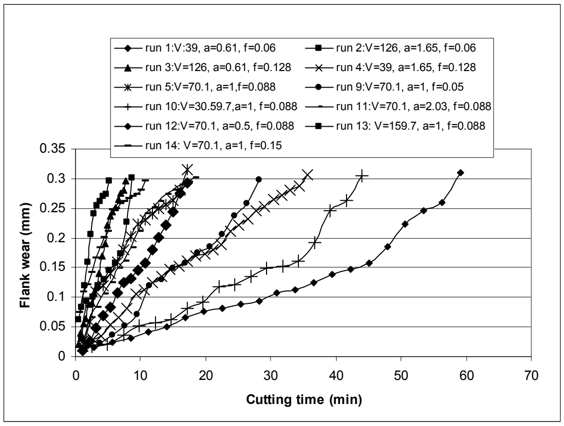

Fig 2: Flank wear versus cutting time

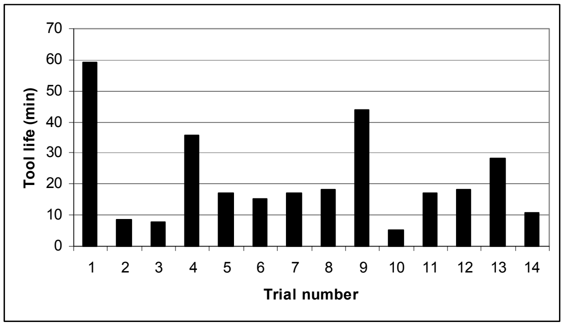

Fig 3: Tool life results of different cutting conditions

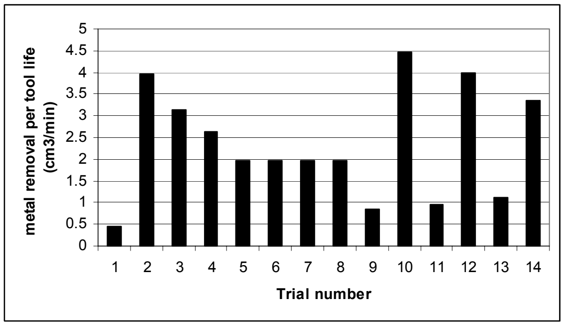

Fig 4: Metal removal per tool life at different cutting conditions.

4.2 First-Order Tool Life Model

The first-order model based on the trial number 1 to 14 in Table 3 is as follows:

$$\hat{y} = 2.9 - 0.81x_1 - 0.038x_2 - 0.25x_3 \tag{7}$$

By substituting (6) into (7) the tool life first-order model is as follows:

$$T = 1274\, V^{-1.381}\, \mathrm{a}^{-0.076}\, f^{-0.67} \tag{8}$$

Table 4: Analysis of variance for the first-order tool life model

Source	SS	DF	MS	F Value	Prob > F
Model	5.738	3	1.913	83.39	< 0.0001
x_1	5.229	1	5.229	227.96	< 0.0001
x_2	0.012	1	0.012	0.51	0.4905
x_3	0.498	1	0.498	21.69	0.0009
Residual	0.229	10	0.023		
Lack of Fit	0.214	7	0.031	6.00	0.0845
Pure Error	0.015	3	0.005		
Cor Total	5.968	13			

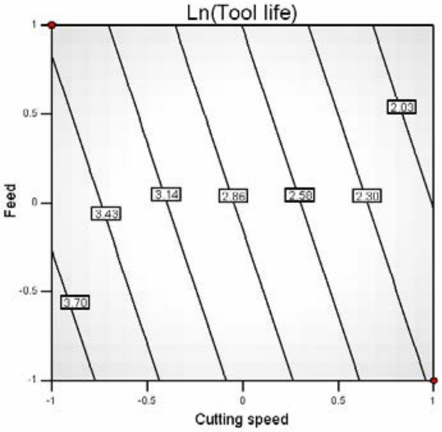

Fig 5: Contours of Cutting speed – feed plane of first-order tool life model at axial depth of cut = 1 (coded factor).

The analysis of variance for first-order tool life model is shown in Table 4. The *model F-value* of 83.39% implies that the model is significant. There is only 0.001% chance that a *Model F-Value* this large could occur due to noise. The ratio of lack of fit to pure error is 6.0. Therefore, the model is adequate. From (8) we can affirm that the tool life increases with the increase of cutting speed, axial depth of cut, and feed. The axial depth of cut has the most significant effect on tool life, followed by feed and cutting speed. The 95% confidence interval of first-order model in Table 4 affirms that the axial depth of cut has insignificant effect on tool life.

4.3 Second-Order Tool Life Model

The second-order tool life model based on the trial number 1 to 14 in Table 3 is as follows:

$$\begin{aligned}\hat{y} = {} & 2.8 - 0.76x_1 - 0.021x_2 - 0.34x_3 - 0.014x_1^2 \\ & + 0.065x_2^2 - 0.056x_3^2 - 0.19x_1x_2 + 0.12x_1x_3 + 0.1x_2x_3\end{aligned} \tag{9}$$

Table 5: Analysis of variance for the second-order tool life model

Source	SS	DF	MS	F Value	Prob > F
Model	5.91	9	0.66	47.83	0.0010
x_1	2.30	1	2.30	167.42	0.0002
x_2	0.00	1	0.00	0.13	0.7329
x_3	0.47	1	0.47	34.52	0.0042
x_1^2	0.00	1	0.00	0.10	0.7647
x_2^2	0.03	1	0.03	2.22	0.2103
x_3^2	0.02	1	0.02	1.69	0.2637
x_1x_2	0.07	1	0.07	5.25	0.0838
x_1x_3	0.03	1	0.03	2.08	0.2226
x_2x_3	0.02	1	0.02	1.47	0.2921
Residual	0.05	4	0.01		
Lack of Fit	0.04	1	0.04	7.78	0.0685
Pure Error	0.02	3	0.01		
Cor Total	5.97	13			

The analysis of variance for second-order tool life model is shown in Table 5. The *model F-value* of 47.83% implies that the model is significant. There is only 0.01% chance that a *Model F-Value* this large could occur due to noise. The ratio of lack of fit to pure error is 7.78. Therefore, the model is adequate. Cutting speed has the most significant effect on tool life followed by feed. From the analysis of variance in Table 5 give evidence that axial depth of cut has insignificant effect on tool life.

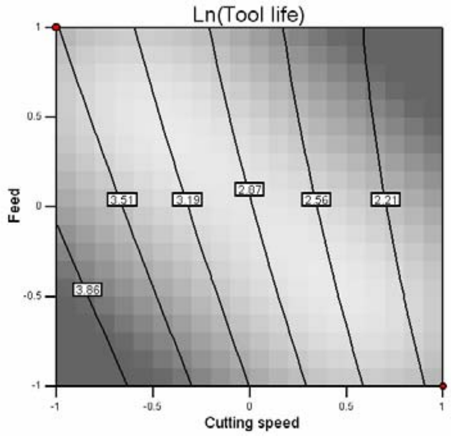

Fig 6: Contours of Cutting speed – feed plane of second-order tool life model at axial depth of cut = 1 (coded factor).

5. CONCLUSIONS

The following conclusions can be drawn from this study:

1. Small central composite design has successfully proved to be a successful technique to assess the tool life in end-milling of titanium alloy Ti-6Al-4V using uncoated WC-Co inserts under dry conditions.
2. The tool life models show that the cutting speed is 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.
3. From the tool life first-order model, it is found that an increase of cutting speed, axial depth of cut and feed by 100%, will lead to reduction of tool life by 70%, 27%, and 37%, respectively.
4. The variance analysis for the second-order model shows that interaction terms and the square terms are statistically insignificant.

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