# Tool Life Prediction by Response Surface Methodology for End Milling Titanium Alloy Ti–6Al–4V Using PCD 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 PCD 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 models and develop the contours. The adequacy of the predictive model was verified using analysis of variance (ANOVA) at 95% confidence level.**

*Keywords – PCD, Tool life, Ti-6Al-4V,response surface*

## I. 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 temperature, 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]. Ginta et al [11] used response surface methodology in assessing tool life in end milling titanium alloy Ti-6Al-4V with uncoated WC-Co inserts. They 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.

The main objective of the current work was to establish the tool life models of polycrystalline diamond (PCD) 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.

## II. MATHEMATICAL MODEL

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

$$T = CV^{k}a^{m}f_{z}^{l} \tag{1}$$

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:

$$\ln T = \ln C + k \ln V + m \ln a + l \ln f \tag{2}$$

The linear model of (2) is:

$$y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \tag{3}$$

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* $\beta_3$ are the parameters to be estimated. Equation (3) can be expressed as:

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

where, 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:

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

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.

## III. 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:

$$x_1 = \frac{\ln V - \ln 126}{\ln 175 - \ln 126} \qquad x_3 = \frac{\ln f_z - \ln 0.088}{\ln 0.128 - \ln 0.088}$$
$$x_2 = \frac{\ln a - \ln 1}{\ln 1.65 - \ln 1} \tag{6}$$

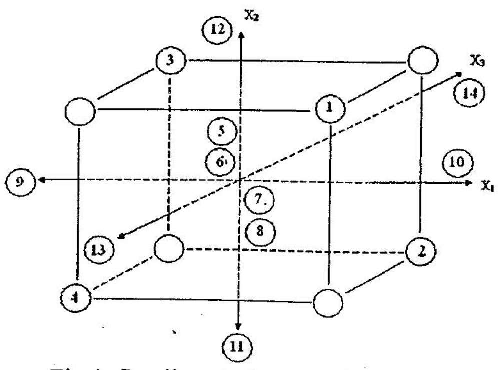



Fig.1. Small central composite design

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, $V$ (m/min) | 80.53 | 92 | 126.9 | 175 | 200 |
| $x_2$, axial depth of cut, $a$ (mm) | 0.5 | 0.61 | 1.00 | 1.65 | 2.03 |
| $x_3$, feed, $f_t$ (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. PCD inserts 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 100 mm to 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. 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.

## IV. RESULTS AND DISCUSSION

The results of tool life in end milling Ti-6Al-4V with PCD inserts for different cutting conditions for all the 14 trial runs with central composite design are shown in Table 2. Flank wear and cutting length distributions are shown in Fig.2. Fit and summary test has been carried out by utilizing the Design-Expert 6.0.8 software to get the best equation for the model and presented in Table 3. From the fit and summary test in Table 3, we can conclude that second-order model is the most suitable fit for modeling the tool life. However, first-order model is also adequate tool life predictions in end milling Ti-6Al-4V using PCD inserts.

The first-order model of the tool life obtained from experimental data in Table 2 is as follows:

$$\hat{y} = 2.21 - 0.46x_1 - 0.15x_2 - 0.2x_3 \qquad (7)$$

Equation (7) is then transformed using the transformation equation (6) to provide the tool life (min) as a function of the cutting speed $v$ (m/min), axial depth of cut (mm) and feed (mm/tooth) as follows:

$$T = 943\ V^{-1.23}\ d^{-0.3}\ f^{-0.53} \qquad (8)$$

Equation (8) indicates that an increase in the cutting speed, axial depth of cut and feed decreases the tool life. Cutting speed has the most effect on tool life, followed by feed and axial depth of cut. From the ANOVA test in Table 4, the model is adequate (Prob > F of the model is 0.036). And it is also indicated that cutting speed has significant effect on tool life because the value of Prob > F is 0.0108 (below 0.05). This equation is valid for end milling (full immersion) at room temperature machining within the range of the cutting speed $V$, axial depth of cut $d$ and feed are 80.5 $\le V \le$ 200 m/min, 0.5 $\le d \le$ 2.03 mm, and 0.05 $\le f \le$ 0.15 mm/tooth, respectively.

The second-order model for tool life in its transformation state is given as:

$$\hat{y} = 2.53 - 0.21x_1 - 0.15x_2 - 0.2x_3 + 0.31x_2^2 - 0.24x_3^2 + 0.5x_2x_3 \qquad (8)$$

From the ANOVA test in Table 5, the calculated Prob > F value" of the second-order model was 0.0002. Hence, the model is adequate. From Table 5, it is also affirmed that cutting speed, axial depth of cut, and feed have significant effects on tool life. Interaction effects between axial depth of cut and feed has also significant effect on tool life. Fig. 5a and 5b show the contour of tool life in cutting speed-feed plane and three dimensional response surface contour, respectively.

Table 2. Experimental results

| No | Coding of levels | | | Tool life (min) |
|---|---|---|---|---|
| | $X_1$ | $X_2$ | $X_3$ | |
| 1 | -1 | -1 | -1 | 21.5 |
| 2 | 1 | 1 | -1 | 3.77 |
| 3 | 1 | -1 | 1 | 3.83 |
| 4 | -1 | 1 | 1 | 11.2 |
| 5 | 0 | 0 | 0 | 11.22 |
| 6 | 0 | 0 | 0 | 14.05 |
| 7 | 0 | 0 | 0 | 13.11 |
| 8 | 0 | 0 | 0 | 10.05 |
| 9 | -1.414 | 0 | 0 | 18.17 |
| 10 | 1.414 | 0 | 0 | 10.12 |
| 11 | 0 | -1.414 | 0 | 7.6 |
| 12 | 0 | 1.414 | 0 | 2.4 |
| 13 | 0 | 0 | -1.414 | 10 |
| 14 | 0 | 0 | 1.414 | 5.2 |

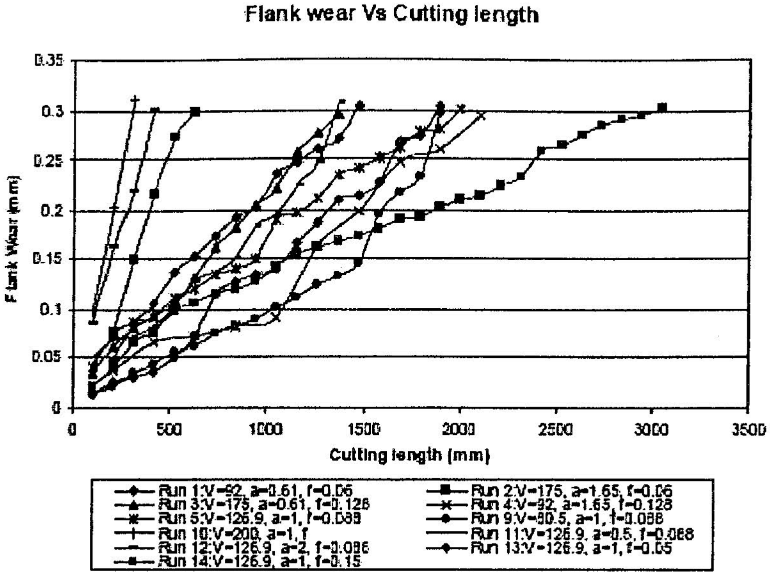



Fig. 2. Flank wear and cutting length distribution

Table 3. Fit and Summary test results

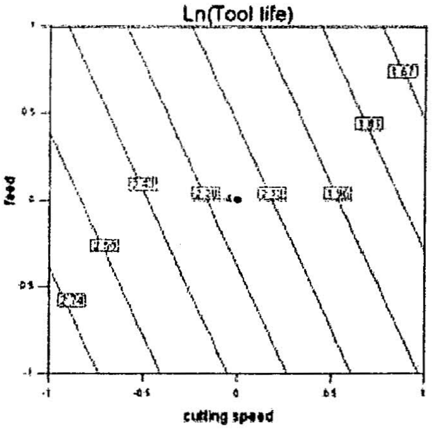
| Source | Sum of Squares | DF | Mean Square | F Value | Prob > F | |
|---|---|---|---|---|---|---|
| Mean | 68.3663985 | 1 | 68.3664 | | | |
| Linear | 2.14378407 | 3 | 0.714595 | 4.211495 | 0.0362 | |
| 2FI | 0.50574988 | 3 | 0.168583 | 0.990815 | 0.4506 | |
| Quadratic | 1.11511761 | 3 | 0.371706 | 19.58806 | 0.0075 | Suggested |
| Cubic | 0.00723994 | 1 | 0.00724 | 0.316317 | 0.6131 | Aliased |
| Residual | 0.06866465 | 3 | 0.022888 | | | |
| Total | 72.2069547 | 14 | 5.15764 | | | |

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

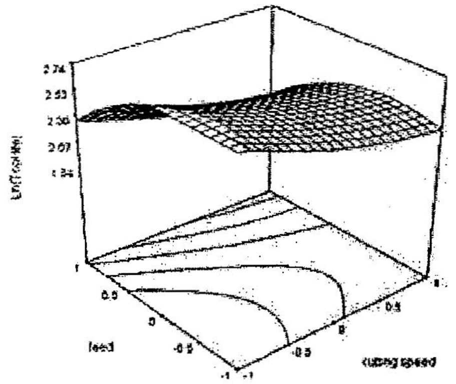
| Source | Sum of Squares | DF | Mean Square | F Value | Prob > F | |
|---|---|---|---|---|---|---|
| Model | 2.143784 | 3 | 0.714595 | 4.211495 | 0.0362 | significant |
| $x_1$ | 1.657754 | 1 | 1.657754 | 9.770044 | 0.0108 | |
| $x_2$ | 0.181385 | 1 | 0.181385 | 1.069001 | 0.3255 | |
| $x_3$ | 0.304645 | 1 | 0.304645 | 1.79544 | 0.2099 | |
| Residual | 1.696772 | 10 | 0.169677 | | | |
| Lack of Fit | 1.628107 | 7 | 0.232587 | 10.16186 | 0.0416 | Not significant |
| Pure Error | 0.068665 | 3 | 0.022888 | | | |
| Cor Total | 3.840556 | 13 | | | | |

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

| Source | Sum of Squares | DF | Mean Square | F Value | Prob > F | |
|---|---|---|---|---|---|---|
| Model | 3.752098 | 7 | 0.536014 | 36.35728 | 0.0002 | significant |
| $x_1$ | 0.171264 | 1 | 0.171264 | 11.61663 | 0.0143 | |
| $x_2$ | 0.181385 | 1 | 0.181385 | 12.30317 | 0.0127 | |
| $x_3$ | 0.304645 | 1 | 0.304645 | 20.66377 | 0.0039 | |
| $x_1^2$ | 0.047114 | 1 | 0.047114 | 3.195714 | 0.1241 | |
| $x_2^2$ | 0.678679 | 1 | 0.678679 | 46.03409 | 0.0005 | |
| $x_3^2$ | 0.407076 | 1 | 0.407076 | 27.61155 | 0.0019 | |
| $x_2x_3$ | 0.493197 | 1 | 0.493197 | 33.45303 | 0.0012 | |
| Residual | 0.088458 | 6 | 0.014743 | | | |
| Lack of Fit | 0.019793 | 3 | 0.006598 | 0.288258 | 0.8329 | not significant |
| Pure Error | 0.068665 | 3 | 0.022888 | | | |
| Cor Total | 3.840556 | 13 | | | | |




(a)




(b)

Fig. 3.Tool life contour in end milling at axial depth of cut 1 mm at : (a) Cutting speed-feed plane, (b), Three-dimensional response surface.

## V. 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 PCD 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. The second-order model can be used to see the interaction effects between the cutting parameters.
4. The variance analysis for the second-order model shows that most of the interaction terms and the square terms are statistically insignificant.

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## REFERENCES

[1] Z.A. Zoya, R. Krisnamurthy, The performance of CBN tools in the machining of titanium alloys, Journal of Mat. Process. Technology 100, pp. 80 – 86, 2000.

[2] L.N. Lopez de lacalle, J. Perez, J.I. Llorente, J. A Sanchez, Advanced cutting conditions for the milling of aeronautical alloys,"Journal of Mater. Process. Technology 100, pp. 1 – 11, 2000.

[3] J.E. Kaye, D.H. Yan, N. Popplewell, S. Balakrishnan, Predicting tool flank wear using spindle speed change, Int. J. Mach. Tools Manufact. Vol. 35 No. 9, pp 1309 – 1320, 1995.

[4] M. Alauddin, M.A. El Baradie, M.S.J. Hashmi, Optimization of surface finish in end milling Inconel 718, Journal of Mater. Process and Technology 56, pp. 54 – 65, 1996.

[5] Kuang- Hua Fuh, Ren-Ming Hwang, A predicted milling force model high-speed end milling operation, Int. J. Mech. Tools Manufact. Vol. 37 No. 7, pp. 969 – 979, 1997.

[6] I.A. Choudhury, M.A. El-Baradie, Tool-life prediction model by design of experiments for turning high strength steel (290 BHN), Journal of Mater. Process. And Technology 77, pp. 319 – 326, 1998.

[7] I.A. Choudhury, M.A. El-Baradie, Machinability assessment of Inconel 718 by factorial design of experiment coupled with response surface methodology, Journal of Material Processing and Technology 95, pp. 30 – 39, 1999.

[8] Mansour, H. Abdalla, Surface roughness model for end milling: a semi-free cutting carbon casehardening steel (EN32) in dry condition," Journal of Materials Processing Technology 124, pp. 183 – 191, 2002.

[9] H. Oktem, T. Erzurumlu, H. Kurtaran, Application of response surface methodology in the optimization of cutting conditions for surface roughness," Journal of Material Processing and Technology 170, pp. 11 – 16, 2005.

[10] S. Sharif, A.S. Mohruni, M.Y. Noordin, V.C. Vencatesh, Optimization of surface roughness prediction model in end milling titanium alloy (Ti-6Al-4V), Proceeding of ICOMAST, pp. 55 – 59, 2006.

[11] Turnad L. Ginta, A.K.M. Nurul Amin, A. N. M. Karim, "Tool life prediction by response surface methodology for end milling titanium alloy Ti–6Al–4V using uncoated carbide inserts", 7th International Conference on Mechanical Engineering, ICME Dhaka, Bangladesh, 2007