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Tool Life Assessment in End Milling Titanium Alloy (Ti–6Al–4V) Using PCD Inserts

Turnad L. Ginta[a*], A.K.M. Nurul Amin[a], M.A. Lajis[b], A.N.M. Karim[b], Agus G.E. Sutjipto[a]

a Department of Manufacturing and Material Engineering, Faculty of Engineering, IIUM, Jalan Gombak, 50278 Kuala Lumpur Malaysia
b Department of Mechanical Engineering, Faculty of Engineering, IIUM, Jalan Gombak, 50278 Kuala Lumpur Malaysia

Abstract

This paper presents the investigation for assessment of tool life of PCD inserts in end milling of titanium alloy Ti-6Al-4V under dry conditions. Small central composite design (CCD) was employed to design the experiments and to develop the models which correlate tool life and the primary cutting parameters such as cutting speed, axial depth of cut and feed values. The range which is used in this study for cutting speed, axial depth of cut, and feed, are 80.5 – 200 m/min, 0.5 – 2.0 mm, and 0.05 – 0.15 mm/tooth, respectively. Design expert package software was employed to establish the tool life models and the adequacy of the models were verified using analysis of variance at 95% of confidence interval. From the models, it was affirmed that cutting speed has the most significant effect on tool life, followed by feed and axial depth of cut

KEYWORDS : Tool life; End milling; Response surface methodology, PCD,Ti – 6Al – 4V

1. Introduction

Titanium alloys are widely used in many areas because of their superior mechanical properties, heat resistance and corrosion resistance. Though the initial application of titanium alloys have been in aerospace industries, there is a growing trend in their applications in the industrial sector, which includes petroleum refining, chemical and food processing, surgical implantation, nuclear waste storage, automotive and marine applications [1]. Despite the increased usage and production of titanium and its alloys, these alloys fall under the category of the most difficult to machine materials. However, titanium alloys are extremely difficult to machine. During the machining, tool wear progresses rapidly due to high cutting temperature and strong adhesion between the tool and the workpiece materials. Additionally, the low modulus of elasticity of titanium alloys and its high strength at elevated temperature further impair its machinability [2]. Another reason for poor machinability of titanium alloys is their tendency to form localized shear bands during machining [3-4].

The chemical reactivity of titanium alloys with tool materials and their consequent welding by adhesion onto the cutting tool during machining leads to excessive chipping and/or premature tool failure and poor surface finish [5].

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 [6]. 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 [7]. 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

Corresponding Author: Turnad L. Ginta, Department of Manufacturing and Materials Engineering, Faculty of Engineering, International Islamic University Malaysia,

assessing machinability, some researchers have tried to employ response surface methodology to design their experimentations, and to establish the models. Kaye *et al* [8] 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* [9] 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 [10]. 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 [11]. 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 [12]. 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 [13]. Oktem *et al* used response surface methodology with a developed genetic algorithm (GA) in the optimization of cutting conditions for surface roughness [14]. 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 [15].

The main objective of the current work was to assess the tool life of polycrystalline diamond 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:

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

Where, T is the predicted tool life (min), 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 Eq. (1) can be expressed as:

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

The linear model of Eq. (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 β_0, β_1, β_2, *and* β_3 are the parameters to be estimated. Eq. (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, ŷ 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:

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

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. Experimental 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 ± $\sqrt{2}$ 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 Eq. (4) and Eq. (5) were obtained from the following transforming equations:

$$x_1 = \frac{\ln V - \ln 126.9}{\ln 175 - \ln 126.9}$$

$$x_3 = \frac{\ln f_z - \ln 0.088}{\ln 0.128 - \ln 0.088}$$

$$x_2 = \frac{\ln a - \ln 1}{\ln 1.65 - \ln 1} \qquad (6)$$

Table 2 presents the experimental design in coding of level and actual values.

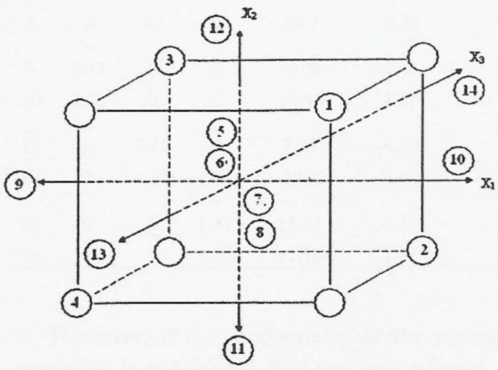

Fig. 1. Small central composite design.

3.2 *Experimental works*

End milling tests were conducted on Vertical Machining Centre (ZPS MCFV 1060 LR) 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 (17 04 08E-P6-NL CD10) 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 and tool life results are presented in Table 3.

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, d (mm)	0.5	0.61	1	1.65	2.03
x_3, feed, f (mm/tooth)	0.05	0.06	0.088	0.128	0.15

Table 2
Experimental design in coding of level and actual values

No	Coding of Level			V (m/min)	a (mm)	f (mm/tooth)
	X_1	X_2	X_3			
1	-1	-1	-1	92	0.61	0.060
2	1	1	-1	175	1.65	0.060
3	1	-1	1	175	0.61	0.128
4	-1	1	1	92	1.65	0.128
5	0	0	0	126.9	1	0.088
6	0	0	0	126.9	1	0.088
7	0	0	0	126.9	1	0.088
8	0	0	0	126.9	1	0.088
9	-1.41	0	0	80.5	1	0.088
10	1.41	0	0	200	1	0.088
11	0	-1.41	0	126.9	0.5	0.088
12	0	1.41	0	126.9	2.03	0.088
13	0	0	-1.41	126.9	1	0.050
14	0	0	1.41	126.9	1	0.150

4. Results and discussion

4.1 Tool life analysis

The tool life, metal removal, and metal removal per tool life data are given at Table 3. An increase in feed and depth of cut causes a decrease in the tool life. Fig. 2 shows that cutting at lower feed value will give a longer tool life. A decrease in feed, will give a significant effect on increase of tool life. But, axial depth of cut will not give a significant effect on tool life. Fig. 3 shows the graph of average flank wear at constant feed. This figure also affirms that of the axial depth of cut will not give a significant effect on tool life. An increase in cutting speed will lead to a significant reduction of tool life as shown in Fig. 4. Fig. 5 and Fig. 6 shows that trial number 1 has the longest tool life (21.5 min) and the highest volume of metal removal (23.06 cm^3/min) with cutting speed, axial depth of cut and feed at 92 m/min, 0.61 mm and 0.06 mm/tooth, respectively.

Table 3
Experimental results

No	Coding of Level			Metal removal (cm^3)	Tool life (min)	Metal removal/tool life (cm^3/min)
	X_1	X_2	X_3			
1	-1	-1	-1	23.06	21.5	1.07
2	1	1	-1	6.62	1.2	5.52
3	1	-1	1	3.18	0.73	4.35
4	-1	1	1	13.18	2.13	6.19
5	0	0	0	7.50	2.11	3.56
6	0	0	0	8.93	2.51	3.56
7	0	0	0	11.02	3.1	3.56
8	0	0	0	12.7	3.57	3.56
9	-1.41	0	0	16.79	7.44	2.26
10	1.41	0	0	10.43	1.86	5.61
11	0	-1.41	0	8.39	4.72	1.78
12	0	1.41	0	17.4	2.41	7.22
13	0	0	-1.41	16.41	8.12	2.02
14	0	0	1.41	11.58	1.91	6.06

However, if the productivity of the machining operation is considered, this run only gives a 1.07 cm^3/min for metal removal per tool life value. Different result was shown by the trial number 12 which give only 2.41 min for tool life and 17.4 cm^3 metal removed. Consequently, it has a 7.22 cm^3/min for metal removal per tool life value. We can affirm from the Fig. 7 that trial number 12 has the best productivity as observed in the experimentation.

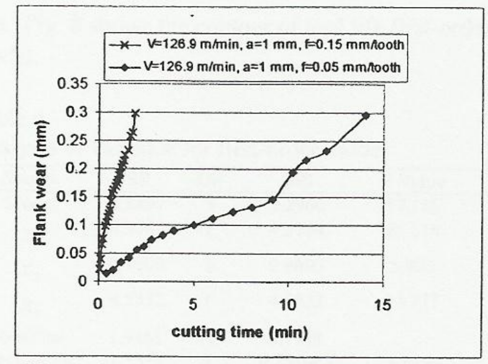

Fig. 2. Average flank wear versus cutting time at different feed.

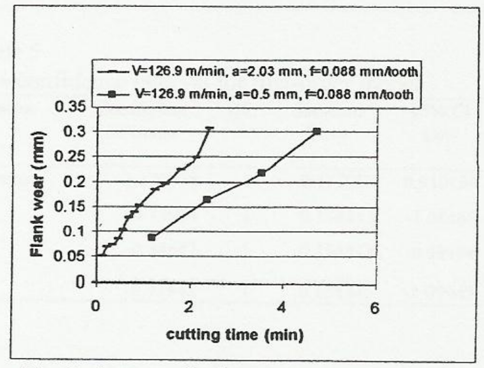

Fig. 3. Average flank wear versus cutting time at different axial depth of cut.

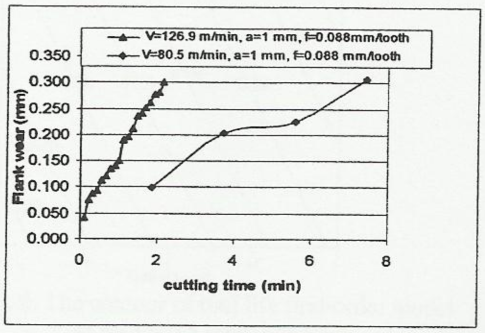

Fig. 4. Average flank wear versus cutting time at different cutting speed.

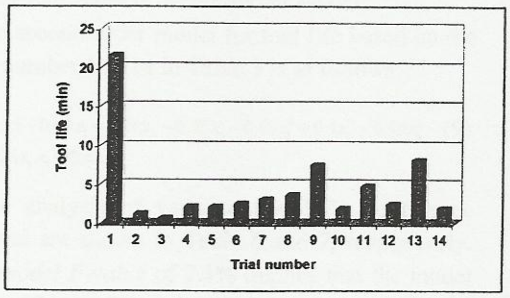

Fig. 5. Tool life for all trial number.

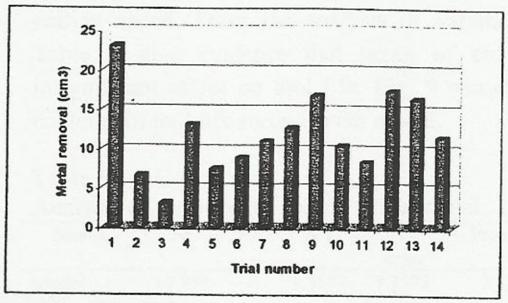

Fig. 6. Metal removal for all trial number.

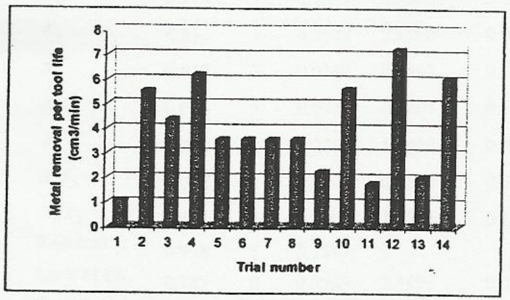

Fig. 7. Metal removal per tool life for all trial number.

4.2 Development of first-order model

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

$$\hat{y} = 1.17 - 0.74x_1 - 0.35x_2 - 0.75x_3 \qquad (7)$$

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

$$T = 1754V^{-2.31}\, d^{-0.75}\, f^{-2.0} \qquad (8)$$

The analysis of variance and 95% confidence interval are shown in Table 4 and 5, respectively. The *model F-value* of 17.2 % implies that the model is significant. There is only 0.03% chance that a *Model F-Value* this large could occur due to noise. The ratio of lack of fit to pure error is 4.7. Therefore, the model is adequate. From Eq. (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 cutting speed has insignificant effect on tool life. From Eq. (8) we can also affirm that cutting speed has the most significant effect on decreasing tool life, followed by feed and axial depth of cut. From Table 4, it is known that cutting speed and feed will have a significant effect on tool life, meanwhile, axial depth of cut has almost significant effect on tool life. Fig. 8 shows the contour of tool life first-order model.

Table 4
Analysis of variance for first-order model

Source	SS	DF	MS	F Value	Prob > F
Model	9.8897	3	3.2966	17.186	0.0003
x_1	4.3764	1	4.3764	22.816	0.0007
x_2	0.9600	1	0.9600	5.005	0.0492
x_3	4.5532	1	4.5532	23.737	0.0006
Residual	1.9181	10	0.1918		
Lack of Fit	1.7572	7	0.251042	4.682	0.1160
Pure Error	0.1608	3	0.053607		
Cor Total	11.807	13			

Table 5
95% confidence interval for first-order model

Factor	Coefficient Estimate	DF	Standard Error	95% CI Low	95% CI High
Intercept	1.170934	1	0.117051	0.910129	1.431739
x_1	-0.73964	1	0.154843	-1.08465	-0.39462
x_2	-0.34642	1	0.154843	-0.69144	-0.00141
x_3	-0.75442	1	0.154843	-1.09943	-0.40941

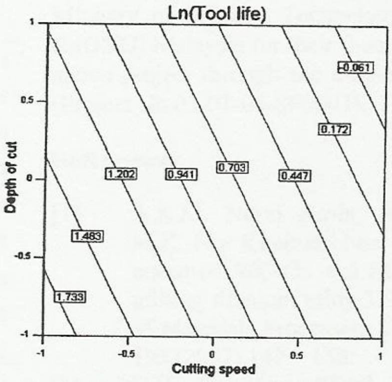

Fig. 8. The contour of tool life first-order model at feed = 0.5 (coded factor).

4.3 Development of second-order model

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

$$\hat{y} = 1.15 - 0.49x_1 - 0.24x_2 - 0.75x_3 - 0.05x_1^2 + 0.1x_2^2 - 0.19x_3^2 - (9)$$
$$+ 021x_1x_3 + 0.5x_2x_3$$

The analysis of variance and 95% confidence interval are shown in Table 6 and 7, respectively. The *model F-value* of 7.1% implies that the model is significant. There is only 2 % chance that a *Model F-Value* this large could occur due to noise. The ratio of lack of fit to pure error is 7.34. Therefore, the model is adequate. Feed has the most significant effect on tool life followed by cutting speed. From the analysis of variance in Table 5 give evidence that depth of cut has insignificant effect on tool life. Fig. 9 shows the contours of tool life second-order model.

Table 6
Analysis of variance for second-order model

Source	SS	DF	MS	F Value	Prob > F
Model	10.859	8	1.3573	7.1533	0.0222
x_1	0.960	1	0.9609	5.0638	0.0742
x_2	0.228	1	0.2287	1.2053	0.3223
x_3	4.553	1	4.5532	23.995	0.0045
x_1^2	0.018	1	0.0182	0.0963	0.7687
x_2^2	0.073	1	0.0733	0.3863	0.5615
x_3^2	0.256	1	0.2567	1.3528	0.2973
x_1x_3	0.092	1	0.0921	0.4854	0.5170
x_2x_3	0.498	1	0.4980	2.6245	0.1661
Residual	0.948	5	0.1897		
Lack of Fit	0.787	2	0.3939	7.3493	0.0698
Pure Error	0.160	3	0.0536		
Cor Total	11.807	13			

Table 7
95% confidence interval for second-order model

Factor	Coefficient estimate	DF	Standard Error	95% CI Low	95% CI High
Intercept	1.1496	1	0.207669	0.615862	1.683525
x_1	-0.4901	1	0.217806	-1.05002	0.069758
x_2	-0.2391	1	0.217806	-0.79901	0.320765
x_3	-0.7544	1	0.154012	-1.15032	-0.35852
x_1^2	-0.0499	1	0.16086	-0.46345	0.36356
x_2^2	-0.0999	1	0.16086	-0.51349	0.313518
x_3^2	0.1871	1	0.16086	-0.2264	0.600605
x_1x_3	0.2146	1	0.308023	-0.5772	1.006402
x_2x_3	0.4990	1	0.308023	-0.29279	1.290812

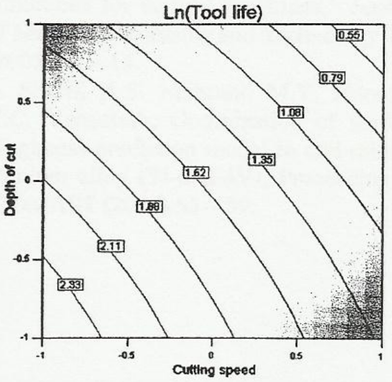

Fig. 9. The contour of tool life second-order model at feed = - 0.5 (coded factor).

5. Conclusion

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 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 50%, will lead to the reduction of tool life by 60%, 25%, and 50%, 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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