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Application of Response Surface Methodology in the Development of Tool Life Prediction Models when End Milling Ti-6Al4V.

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Abstract– **This paper deals with development of prediction models for tool life when end milling titanium alloy, Ti-6Al4V using TiAlN-coated solid carbide tools under flood condition. Primary machining parameters such as cutting speed, feed and radial rake angle were used as independent variables. Three main models such as 3F-model, 1st CCD-model and 2nd CCD-model, were observed using response surface methodology (RSM) in determining the optimum cutting conditions for a particular tool life interval. ANOVA was applied to prove adequacy of the predictive models.**

Keywords– Tool life models, End milling, Titanium Alloys, Response Surface Methodology.

I. INTRODUCTION

The trend in using titanium as aerospace materials in the airframe structure is increasing, mainly due to its great resistance to oxidation at elevated temperature, in addition to its low weight-to-strength ratio. Previous studies have shown that titanium and its alloys are considered as difficult to machine material, regardless of the type of tool materials used. This has been attributed to their low thermal conductivity which concentrates heat in the cutting zone (typically less than 25% that of steel), retention of strength at elevated temperatures and high chemical affinity for almost all cutting tool materials [1]-[11].

Machinability of materials provides an indication of its adaptability to be manufactured by a machining process. In general, machinability can be defined as an optimal combination of factors such as low cutting force, high material removal rate, good surface integrity, accurate and consistent workpiece geometrical characteristics, low tool rate and good curl or chip breakdown of chips [12].

Investigations in machinability studies used quite extensive statistical design of experiments (DOE). The DOE refers to the process planning of the experiments so that appropriate data can be analyzed using statistical method, which results in valid and objective conclusions [13]. A large number and a separate set of tests are required for each and every combination of cutting tool and workpiece materials, in order to establish an adequate functional relationship between the tool life and the cutting parameters (cutting speed, feed, and radial rake angle) [14].

The tool deterioration phenomena in end milling cutter is discussed in detail in ISO 8688-2 [16], which was used as reference to determine the tool life criteria. Two categories of cutting conditions in end milling may be considered, which are: (i) cutting condition as a results of which tool deterioration due to wear; and (ii) cutting conditions under which tool deterioration is due to other phenomena such as edge fracture or plastic deformation [17].

Traditionally, investigation of the effect of various cutting parameters on tool life was carried out using one variable at a time approach. However, this study takes other approach which used simultaneous variation of speed, feed and radial rake angle to predict the tool life model when end milling Ti-6Al4V. This approach which was pioneered by Wu [18] is known as response surface methodology (RSM), where the response of the dependent variable (tool life) is presented as a surface.

II. DEVELOPMENT OF THE MATHEMATICAL MODEL USING RSM

For this purpose, the mathematical model relating to the machining responses and their factors were developed to facilitate the optimization of the machining process.

II.1 POSTULATION OF THE MATHEMATICAL MODELS

It is assumed that the proposed model for the tool life is merely a function of cutting speed V, feed f_z and radial rake angle γ_o. Other factors such as machine tools, stability, entry and exit condition etc are kept constant. Thus the proposed tool life model in end milling Ti-6Al4V can be expressed as

$$T = C.V^{k} f_{z}^{l}.\gamma_{o}^{m}.\varepsilon^{'} \quad (1)$$

where T is the experimental (measured) tool life according to tool life criteria (min^{-1}), V is the cutting speed (m.min^{-1}), f_z is the feed per tooth (mm.tooth^{-1}), γ_o is the radial rake angle (^{o}), $\varepsilon^{'}$ is the experimental error and C, k, l, m are parameters to be estimated using experimental data.

In order to facilitate the determination of constants and exponents, the mathematical model will have to be linearized using logarithmic transformation, and equation (1) can be converted into first order polynomial as

$$\ln T = \ln C + k\ln V + l\ln f_{z} + m\ln \gamma_{o} + \ln \varepsilon^{'} \quad (2)$$

which can also be formed as

$$y = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + \varepsilon \quad (3)$$

and finally can be written as

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

where y is the experimental measured tool life on a natural logarithmic scale, $\hat{y}_1$ is the natural logarithmic value of predicted (estimated) tool life, $x_0 = 1$ (a dummy variable), x_1, x_2 and x_3 are the coded value (natural logarithmic transformation) of V, f_z and γ_o respectively, ε is the natural logarithmic transformation of experimental error ε' and b_0, b_1 and b_3 are the model parameters to be predicted using the experimental data [19].

To investigate the extended observation region, the second order model is also useful when the second order and interaction effect of V, f_z, γ_o are significant. The first order model in equation (4) can be extended to the second order model as

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

where $\hat{y}_2$ is the predicted response based on the experimental measured tool life on a natural logarithmic scale and b values are the parameters, which are to be estimated by method least squares method.

Analyzing of the experimental results was conducted by means of Design Expert 6.0 software [20], while validity of the resulted prediction models, which is used for optimizing the machining process, has to be tested using analysis of variance (ANOVA).

III. EXPERIMENTAL WORKS

Before commencing the experimental tests, a well planed experimentation was essential in order to acquire the relevant data for the development of the mathematical model. Using design of experiments (DOE) the development of mathematical model were started with 2^k-factorial design and stepwise extended to central composite design.

III.1 EXPERIMENTAL DESIGN

First step in developing mathematical model is to consider the 2^k-factorial design with replicated center points as screening tests of the experiments, which employed the first 12 experiments as shown in Fig. **1** [13].

An extended design of 2^3-factorial design is called a second order central composite design (CCD), which was augmented with replicated stars point as shown in Fig. **1**. The number of such repeated measurements affects the distance of the "axial star points" with the factor space. According to previous study [19], the distance of axial star points to the center points α is 1.4142.

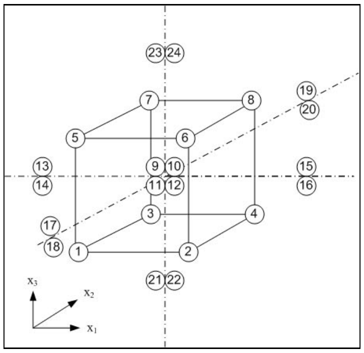


Fig. 1 Design of experiments used in developing mathematical models.

III.2 CODING OF INDEPENDENT VARIABLES

Further step in developing the mathematical models is coding of independent variables by taking into consideration the capacity and limiting cutting conditions of milling machine. The following transforming equation was used.

$$x = \frac{\ln x_n - \ln x_{n0}}{\ln x_{n1} - \ln x_{n0}} \quad (6)$$

where x is the coded variable of any factor corresponding to its natural x_n, x_{n1} is the natural value at the +1 level and x_{n0} is the natural value of the factor corresponding to the base or zero level [14] - [19]. The level of the independent variables and coding identification are illustrated in Table 1.

Table 1 Levels of independent variables for end milling Ti-6Al4V

Independent Variable	Level in coded form				
	-α	-1	0	+1	+α
V (mm.min^{-1}) x_1	124.53	130	144.22	160	167.03
f_z (mm.tooth^{-1}) x_2	0.025	0.03	0.046	0.07	0.083
γ_o (^{o}) x_3	6.2	7.0	9.5	13.0	14.8

III.3 EXPERIMENTAL SET-UP

The tests were carried out with a constant a_a (axial depth of cut) 5 mm and a_e (radial depth of cut) 2 mm under flood conditions with a 6% concentration of water base coolant using MAHO 700S CNC machining center for side milling operation. The grade K-30 solid carbide end mill cutters, with PVD-TiAlN coated which were prepared with different radial rake angle according to DOE, were used for experimentation.

The reference workpiece material was a rectangular bar (110 x 110 x 270 mm) of Ti-6Al4V. Tool life criteria used were $VB_{max} \geq 0.25$ mm, chipping ≥ 0.20 mm and catastro-phic failure.

Tool wear was measured using a Nikon tool makers' microscope with 30x magnification. The measurements of tool wear according to [16] were carried out for each cutting edge at initial cut and continuously after a particular length of cut (depend on wear progressive of each tool) until the end of tool life was achieved.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The tool life experimental results of TiAlN-coated carbide tools are shown in Table 2. The major contributor for wear occurred in end milling Ti-6Al4V were flank wear of the end of the cutting edge and chipping.

IV.1 DEVELOPMENT OF THE TOOL LIFE MODEL USING 2^K-FACTORIAL DESIGNS.

The first 12 trials obtained in Table 2 (see also Fig. **1**) were used for generating the 3F1-model as a screening tests.

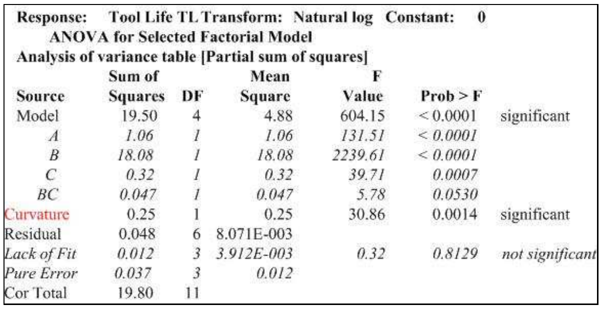
Using Design Expert software with ln transformation, the developed 3F1-tool life model in coded factor can be written as follows

$$\hat{y} = 1.3332 - 0.3643x_1 - 1.5032x_2 + 0.2002x_3 + 0.0764x_2x_3 \tag{7}$$

From Equation (7), it can be recognized that the most significant factor which influenced the tool life, is the feed followed by cutting speed and lastly the radial rake angle. From the ANOVA results shown in Fig. 2, it can be seen that the lack of fit (LOF) of the model is not significant. Thus indicating that Equation (7) was valid for the given cutting conditions, which is side milling of Ti-6Al4V using TiAlN-coated solid carbide tools under flood conditions with the following ranges of cutting speed V, feed per tooth f_z and radial rake angle γ_o : $130 \leq V \leq 160$m.min^{-1}; $0.03 \leq f_z \leq 0.07$ mm.tooth^{-1}; $7 \leq \gamma_o \leq 13$ (^{o}) respectively.

Table 2 Tool life results for TiAlN-coated carbide tools

Std. Order	Type	Cutting Speed V (m.min^{-1})	Feed per tooth (mm.th^{-1})	Radial rake angle (^{o})	Tool Life (min)
1	Factorial	-1	-1	-1	20.81
2	Factorial	1	-1	-1	10.91
3	Factorial	-1	1	-1	0.89
4	Factorial	1	1	-1	0.46
5	Factorial	-1	-1	1	29.08
6	Factorial	1	-1	1	12.81
7	Factorial	-1	1	1	1.65
8	Factorial	1	1	1	0.75
9	Center	0	0	0	5.09
10	Center	0	0	0	5.86
11	Center	0	0	0	5.26
12	Center	0	0	0	4.48
13	Axial	-1.4142	0	0	11.43
14	Axial	-1.4142	0	0	11.36
15	Axial	1.4142	0	0	3.54
16	Axial	1.4142	0	0	3.58
17	Axial	0	-1.4142	0	13.79
18	Axial	0	-1.4142	0	14.03
19	Axial	0	1.4142	0	0.21
20	Axial	0	1.4142	0	0.22
21	Axial	0	0	-1.4142	5.20
22	Axial	0	0	-1.4142	5.23
23	Axial	0	0	1.4142	8.78
24	Axial	0	0	1.4142	8.48



Response: Tool Life TL Transform: Natural log Constant: 0

ANOVA for Selected Factorial Model

Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	19.50	4	4.88	604.15	< 0.0001	significant
A	*1.06*	*1*	*1.06*	*131.51*	*< 0.0001*	
B	*18.08*	*1*	*18.08*	*2239.61*	*< 0.0001*	
C	*0.32*	*1*	*0.32*	*39.71*	*0.0007*	
BC	*0.047*	*1*	*0.047*	*5.78*	*0.0530*	
Curvature	0.25	1	0.25	30.86	0.0014	significant
Residual	0.048	6	8.071E-003			
Lack of Fit	*0.012*	*3*	*3.912E-003*	*0.32*	*0.8129*	*not significant*
Pure Error	*0.037*	*3*	*0.012*			
Cor Total	19.80	11				

Fig. 2 ANOVA for 3F-model of TiAlN coated end mill with n_c = 4.

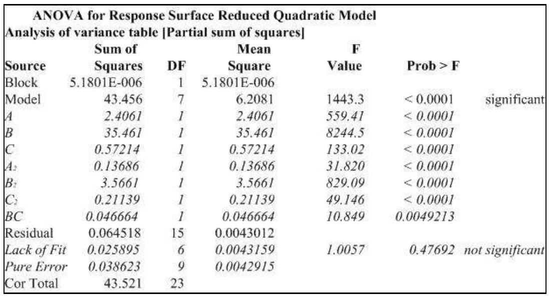
IV.2 DEVELOPMENT OF THE TOOL LIFE MODEL USING 2nd CCD

Another development of the higher order model was conducted employing the CCD, which utilizes 24 experimental results.

The result of the second order model analysis in coded variables is given below,

$$\begin{aligned}\hat{y} &= y - \varepsilon \\ &= 1.6383 - 0.3878\,x_1 - 1.4887\,x_2 + 0.1891\,x_3 \\ &\quad + 0.07637\,x_2 x_3 + 0.10684\,x_1^2 - 0.5451\,x_2^2 + 0.1327\,x_3^2\end{aligned}$$

Result obtained from Equation (8) strengthen the previous effect revealed in Equation (7) that the most significant factor, which influenced the tool life, is the feed followed by cutting speed and radial rake angle. Similar result for the 3F1-model was recorded for the interaction effect and additional quadratic effect occurred in second order CCD model.



ANOVA for Response Surface Reduced Quadratic Model
Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Block	5.1801E-006	1	5.1801E-006			
Model	43.456	7	6.2081	1443.3	< 0.0001	significant
A	*2.4061*	*1*	*2.4061*	*559.41*	*< 0.0001*	
B	*35.461*	*1*	*35.461*	*8244.5*	*< 0.0001*	
C	*0.57214*	*1*	*0.57214*	*133.02*	*< 0.0001*	
A₂	*0.13686*	*1*	*0.13686*	*31.820*	*< 0.0001*	
B₂	*3.5661*	*1*	*3.5661*	*829.09*	*< 0.0001*	
C₂	*0.21139*	*1*	*0.21139*	*49.146*	*< 0.0001*	
BC	*0.046664*	*1*	*0.046664*	*10.849*	*0.0049213*	
Residual	0.064518	15	0.0043012			
Lack of Fit	*0.025895*	*6*	*0.0043159*	*1.0057*	*0.47692*	*not significant*
Pure Error	*0.038623*	*9*	*0.0042915*			
Cor Total	43.521	23				

Fig. 3 ANOVA for second order CCD-model of TiAlN coated end mill with $n_c = 4$.

To check the adequacy of Equation (8), ANOVA was carried out and results are shown in Fig. 3. It is obvious that the LOF of the proposed model is not significant. This implies that Equation (8) is valid for side milling of titanium alloy Ti-6Al4V using TiAlN coated carbide tools under flood conditions with the following ranges of cutting speed V, feed per tooth f_z and radial rake angle γ_o: $124.53 \le V \le 167.03$ (m.min^{-1}); $0.025 \le f_z \le 0.083$ (mm.tooth^{-1}); and $6.2 \le \gamma_o \le 14.8$ (^{o}) respectively.

IV.3 DEVELOPMENT OF THE TOOL LIFE MODEL USING 1st CCD

The second option of tool life for the CCD model is the linear CCD model. The factorial data from Table 2 which is identical with the data for 3F1-model were used to construct this model. This approach was adopted to avoid the accumulative error when too many unused data were taken into account while computing the data.

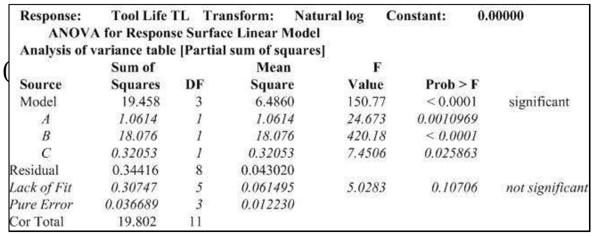
The first order model resulted from the CCD analysis in coded variables is as follow,

$$\hat{y} = 1.4351 - 0.3643x_1 - 1.5032x_2 + 0.2002x_3 \qquad (9)$$

Equation (9) can be transformed using Equation (6), which resulted in the predictive tool life as

$$\hat{T} = 653.113V^{-3.50897} f_z^{-3.54822} \gamma_o^{0.64681} \qquad (10)$$

where $\hat{T}$ is the predicted tool life in (min).

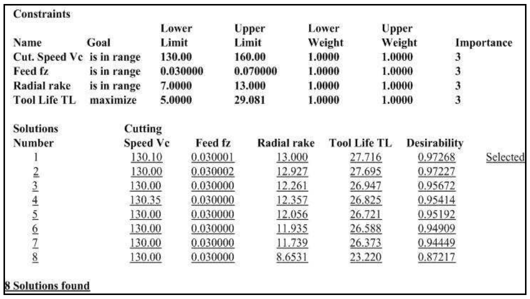


Response: Tool Life TL Transform: Natural log Constant: 0.00000
ANOVA for Response Surface Linear Model
Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	19.458	3	6.4860	150.77	< 0.0001	significant
A	*1.0614*	*1*	*1.0614*	*24.673*	*0.0010969*	
B	*18.076*	*1*	*18.076*	*420.18*	*< 0.0001*	
C	*0.32053*	*1*	*0.32053*	*7.4506*	*0.025863*	
Residual	0.34416	8	0.043020			
Lack of Fit	*0.30747*	*5*	*0.061495*	*5.0283*	*0.10706*	*not significant*
Pure Error	*0.036689*	*3*	*0.012230*			
Cor Total	19.802	11				

Fig. 4 ANOVA for first order CCD-model of TiAlN coated end mill with $n_c = 4$.

For validation of equation (10), the ANOVA was used. From the ANOVA shown in Fig. **4**, the LOF is not significant but the model is significant. It implies that the model can represent the experimental data with acceptable mean square error (MSE). This equation is valid for side milling of Ti-6Al4V using TiAlN-coated solid carbide tools under flood conditions with the following ranges of cutting speed V, feed per tooth f_z and radial rake angle γ_o : $130 \le V \le 160$m.min^{-1}; $0.03 \le f_z \le 0.07$ mm.tooth^{-1}; $7 \le \gamma_o \le 13$ (^{o}) respectively.



Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Cut. Speed Vc	is in range	130.00	160.00	1.0000	1.0000	3
Feed fz	is in range	0.030000	0.070000	1.0000	1.0000	3
Radial rake	is in range	7.0000	13.000	1.0000	1.0000	3
Tool Life TL	maximize	5.0000	29.081	1.0000	1.0000	3

Solutions Number	Cutting Speed Vc	Feed fz	Radial rake	Tool Life TL	Desirability	
1	130.10	0.030001	13.000	27.716	0.97268	Selected
2	130.00	0.030002	12.927	27.695	0.97227	
3	130.00	0.030000	12.261	26.947	0.95672	
4	130.35	0.030000	12.357	26.825	0.95414	
5	130.00	0.030000	12.056	26.721	0.95192	
6	130.00	0.030000	11.935	26.588	0.94909	
7	130.00	0.030000	11.739	26.373	0.94449	
8	130.00	0.030000	8.6531	23.220	0.87217	

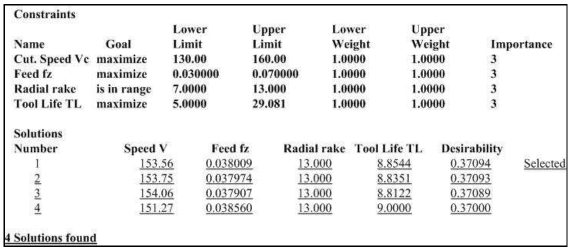
8 Solutions found

Fig. 5 Possible solutions for 3F1-tool life model using TiAlN coated end mill with $n_c = 4$ when V and f_z are in range.

IV.4 OPTIMUM CUTTING CONDITIONS FOR A PARTICULAR TOOL LIFE RANGE USING 3F1-MODEL

To determine which model should be chosen from the three types of obtained tool life models, in finding the optimum cutting conditions for a particular tool life range. It is essential to select the most accurate model gained from the analysis based on the MSE of the three models. It was found that the 3F1-tool life model is the most accurate model compared to others models. Based on the 3F1-tool life model, the possible solutions for the end mill having tool life greater than

5 minutes when cutting speed V and feed f_z is kept in range, are illustrated in Fig. **5**. From the results, it is recognized that the optimum cutting condition for end milling Ti-6Al4V, which fulfill the given constraint, was cutting speed V 130.10 m.min^{-1}, feed per tooth f_z 0.03 mm.tooth^{-1} and radial rake angle γ_o 13^o.



Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Cut. Speed Vc	maximize	130.00	160.00	1.0000	1.0000	3
Feed fz	maximize	0.030000	0.070000	1.0000	1.0000	3
Radial rake	is in range	7.0000	13.000	1.0000	1.0000	3
Tool Life TL	maximize	5.0000	29.081	1.0000	1.0000	3

Solutions

Number	Speed V	Feed fz	Radial rake	Tool Life TL	Desirability	
1	153.56	0.038009	13.000	8.8544	0.37094	Selected
2	153.75	0.037974	13.000	8.8351	0.37093	
3	154.06	0.037907	13.000	8.8122	0.37089	
4	151.27	0.038560	13.000	9.0000	0.37000	

4 Solutions found

Fig. 6 Possible solutions for 3F1-tool life model using TiAlN coated end mill with $n_c = 4$ when V and f_z are maximized.

Another optimum cutting condition for end milling Ti-6Al4V with the following constraints; tool life greater than 5 minutes and cutting speed V and f_z are maximized, which are appropriate for industrial needs, is illustrated in Fig. **6**. Results show that the optimum cutting condition for end milling Ti-6Al4V, which satisfy the specified constraint, was cutting speed V 155.56 m.min^{-1}, feed per tooth f_z 0.038 mm.tooth^{-1} and radial rake angle γ_o 13^o.

V. CONCLUSIONS

Three tool life prediction models were satisfied for describing the tool life when end milling Ti-6Al4V, namely 3F1-model, 1st and 2nd order CCD-models. The most accurate among them was the 3F1-tool life prediction model.

Main effects in linear observation region, which described by 3F1- and 1st order CCD models, showed the same contribution to tool life as compared to the 2nd order CCD tool life model.

Based on the optimization processes, two optimum cutting conditions are revealed for two different objectives of constraints, when end milling Ti-6Al4V.

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REFERENCES

[1]. W. Koenig, "Applied research on the machinability of titanium and its alloys", *Proceeding 47th Meeting of AGARD Structural and Materials Panel, Florence, AGARD CP256, London,* pp. 1-10, 1979.

[2]. R. Komanduri and W.R. Reed, "Evaluation of carbide grades and new cutting geometry for machining titanium alloy", *Wear,* vol. 92, pp. 113-123, 1983.

[3]. P.A. Dearnley and A.N. Gearson, "Evaluation of principal wear mechanism of cemented carbides and ceramics used for machining titanium alloy IMI318", *Materials Science and Technology,* vol. 2, pp.1986.

[4]. M. Wang and Y. Zhang, "Diffusion wear in milling titanium alloys", *Mterial Science and Technology,* vol.4, pp 548-553, 1988.

[5]. A.R. Machado and J. Wallbank, "Machining of titanium and its alloys-a review", *Proceeding of the Institution of Mechanical Engineers,* vol. 204, pp.53-59, 1990.

[6]. A. Jawaid, C.H. Che Haron, A. Fallah, "Tool wear in machining of titanium alloy Ti 6242", *Proceeding of the 3rd International Conference on Progress of Cutting and Grinding, Osaka, Japan, Nov.,* pp. 126-131, 1996.

[7]. E.O. Ezugwu and Z.M. Wang, "Titanium alloys and their machinability – a review", *Journal of Materials Processing Technology,* vol.68, pp.262-274, 1997.

[8]. A. Jawaid, S. Sharif, K. Koksal, "Evaluation of wear mechanism of coated carbide tools when face milling of titanium alloys", *Journal of Materials Processing Technology,* vol. 99, no. 1, pp. 266-274, 2000.

[9]. H. Niemann, Ng. Eu-gene, H. Loftus, A. Sharman, R. Dewes and D. Aspinwall, "The effect of cutting environment and Tool coating when high speed ball nose end milling titanium alloy", *In Metal Cutting and High Speed Machining,* edited by D. Dudzinski, A. Molinari, H. Schulz, pp. 181-189, 2002.

[10]. J.I. Hughes, A.R.C. Sharman and K. Ridgway, "The effect of tool edge preparation on tool life and workpiece surface integrity, *Proceeding of the Institution of Mechanical Engineers,* vol. 218, no. 9, pp. 1113-1123, 2004.

[11]. A.K.M. Nurul Amin, A.F. Ismail, M.K. Nor Khairusshima, "Effectiveness of uncoated WC-Co and PCD inserts in end milling of titanium alloy-Ti-6Al-4V, *Journal of Materials Processing Technology,* vol. 192-193, pp. 147-158, 2007.

[12]. M.Y. Noordin, V.C. Venkatesh, S. Sharif, S. Elting, A. Abdullah, "Application of response surface methodology in describing the performance of coated carbide tools when turning AISI 1045 steel", *Journal of Materials Processing Technology,* vol. 145, no. 1, pp. 46-58, 2004.

[13]. D.C. Montgomery, "Design and Analysis of Experiments, 5th ed. Wiley, New York, 2001.

[14]. I.A. Choudury, M.A. El-Baradie, M.S.J. Hasmi, "Tool life prerdiction model by design of experiments for turning high strength stell (290 BHN)", *Journal of Materials Processing Technology,* vol. 77, no. 1-3, pp. 319-326, 1998.

[15]. I.A. Choudury and M.A. El-Baradie, "Prediction of tool life in end milling by response surface methodology", *Journal of Materials Processing Technology,* vol. 77, no. 1-3, pp. 319-326, 1998.

[16]. ISO 8688-2, Tool life testing in milling, Part 2: End Milling, (E) 1-26, 1989.

[17]. M. Alauddin, M.A. El-Baradie, M.S.J. Hasmi, "Prediction of tool life in end milling by response surface methodology", *Journal of Materials Processing Technology,* vol. 71, no. 1, pp. 456-465, 1997.

[18]. S.M. Wu, "Tool life testing by response surface methodology, part I and part II", transc. ASME, vol. 86, pp. 105-116, 1964.

[19]. S. Sharif, A.S. Mohruni, M.Y. Noordin, "Modeling of tool life when end milling on titanium alloy (Ti-6Al-4V) using response surface methodology, *In Proceeding of 1st International Conference & 7th AUSN/SEED-Net Fieldwise Seminar on Manufacturing and Material Processing*, 14-15 March, Kuala Lumpur, pp.127-132, 2006.

[20]. Design Expert Software 6.0, User's Guide, Technical Manual, Stat-Ease Inc. Minneapolis, MN, 2000.