ICMM 2006

Proceedings of the

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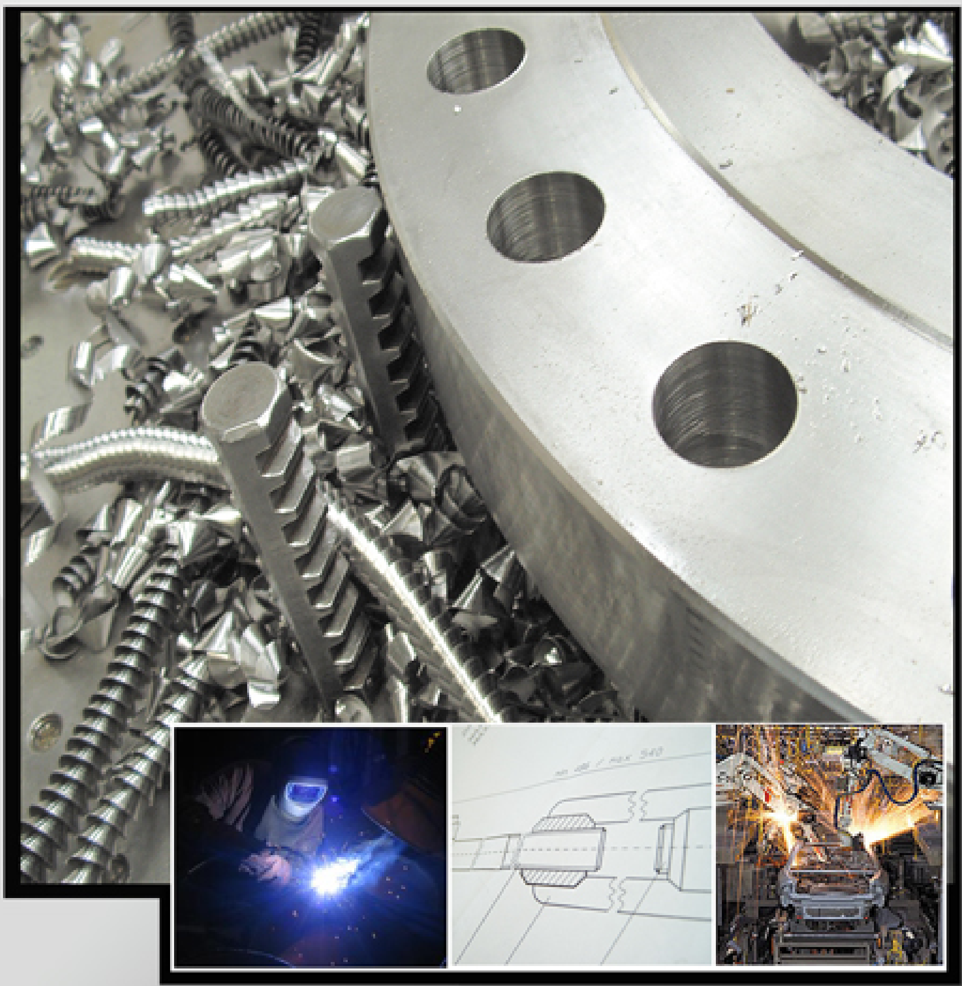

Manufacturing Innovation and Excellence through Research and Development

14-15 March 2006
Kuala Lumpur

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DEPARTMENT OF ENGINEERING DESIGN AND MANUFACTURE
FACULTY OF ENGINEERING, UNIVERSITY OF MALAYA

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Modeling of tool life when end milling on titanium alloy (Ti-6Al-4V) using response surface methodology

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Abstract
This paper reports on the development of the mathematical model for tool life in end milling titanium alloy (Ti-6Al-4V) using uncoated carbide under flood conditions. The models of tool life have been developed in terms of primary machining variables such as cutting speed, feed and radial rake angle by response surface methodology. Response surface contour were constructed in 3D surface using Design Expert 6.0 and used in determining the optimum cutting conditions for a particular tool life range. The adequacy of predictive models was proved by ANOVA.

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

1. INTRODUCTION

The difficulties that are found in the machining of titanium-based alloys are mostly due to the high levels of hardness at high temperature that these materials have, in particular when compared to steels with similar properties. The appropriate selection of tool materials, cutting parameters and coolant lubrication constitutes the basis for safe machining process. Due to low machinability of titanium alloys, selecting the machining conditions and parameters is crucial. The appropriate range of feeds and cutting speeds, which provide a satisfactory tool life, is very limited. [1] [2]

Machinability of material 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 [3].

In machinability studies investigations, statistical design of experiments is used quite extensively. Statistical design of experiment refers to the process planning of the experiment so that appropriate data can be analyzed using statistical methods, resulting in valid and objective conclusions [4] In order to establish an adequate functional relationship between the tool life and the cutting parameters (cutting speed, feed, and radial rake angle), a large of number of tests are needed, requiring a separate set of tests for each and every combination of cutting tool and workpiece material. This increases the total number of tests and as result the experimentation cost also increases [5].

In general, a cutting tool fails either by gradual wear or by fracturing. A detailed discussion on tool deterioration phenomena in end mill cutter can be found in the literature [6]. The cutting conditions in end milling may be considered under two categories, which are (i) condition as a results of which tool deterioration is due to wear; and (ii) conditions under which tool deterioration is due to other phenomena such as edge fracture or plastic deformation. In this study, the tool life in end milling was considered on the basis of flank wear [7].

Most researchers have investigated the effects of various cutting parameters on tool life by the one variable at a time approach. The present study takes into account the simultaneous variation of speed, feed and radial rake angle, and predicts the tool life (response). This approach is known as response surface methodology (RSM), where the response of the dependent variable (tool life) is viewed as a surface, and was pioneered by Wu [8].

2. DEVELOPING OF THE MATHEMATICAL MODEL BY RSM

In this work, mathematical models have been developed using RSM based on experimental results. The purpose of developing mathematical models relating to the machining response and their factor is to facilitate the optimization of the machining process.

2.1 Mathematical Models

Factors which affect the tool life in end milling operations can be seen in [7] However, for particular work tool geometry, the tool life in end milling is assumed to be a function of the primary independent variables such as;

$$\text{Tool life} = f(V, f_z, \gamma_o) \tag{1}$$

where V is the cutting speed (m min^{-1}), f_z is the feed per tooth (mm $tooth^{-1}$) and γ_o is the radial rake angle (^{o}).

The mathematical models commonly used are represented by:

$$T = C\, V^k\, f^l\, \gamma_o^{\,m}\, \varepsilon' \tag{2}$$

where T is the experimental (measured) tool life (min), ε' is the experimental error and C, k, l, m are model parameters to be estimated using experimental data.

To facilitate the determination of constants and exponents, this mathematical model will have to be linearized by performing a logarithmic transformation as follows:

$$\ln T = \ln C + k \ln V + l \ln f_z + m \ln \gamma_o + \ln \varepsilon' \quad (3)$$

which can be written as:

$$y = b_0x_0 + b_1x_1 + b_2x_2 + b_3x_3 + \varepsilon \quad (4)$$

or

$$\hat{y}_1 = y - \varepsilon = b_0x_0 + b_1x_1 + b_2x_2 + b_3x_3 \quad (5)$$

where y is the logarithmic value of the experimental tool life, $\hat{y}_1$ is the logarithmic value of the predictive (estimated) tool life, $x_0 = 1$ (a dummy variable), x_1, x_2 and x_3 are the coded value (logarithmic transformation) of V, f_z and γ_o respectively, ε is the logarithmic transformation of experimental error ε' and b_0, b_1, b_2 and b_3 are the model parameters to be estimated using the experimental data.

To cover the response surfaces which often exhibit some curvature in the normal operating range of the machining conditions, the general second order model of polynomial response is given as below:

$$\hat{y}_2 = y - \varepsilon = b_0x_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_{12} + b_{13}x_{13} + b_{23}x_{23} + b_{11}x_{11}^2 + b_{22}x_{22}^2 + b_{33}x_{33}^2. \quad (6)$$

where $\hat{y}_2$ is the estimated response based on the second order equation. The parameters, i.e. b_i and b_{ij} are to be estimated by method of least squares. Validity of the selected model used for optimizing the process parameters has to be tested using ANOVA.

3. EXPERIMENTAL DETAILS

For developing models based on experimental data, careful planning of experimentation is essential. The factors, considered for experimentation and analysis were cutting speed, feed rate and radial rake angle.

3.1 Experimental design

The design of experimentation has a major effect on the number of the conducted experiments. Therefore it is important to have a well designed set of experiments. In this study, the 2 level factorial design also known as first order model using 3F1-factorial design was used as screening trials of the experiment to determine the significant factors. Furthermore, the factorial points in the design are not replicated. Then it is useful to use additional center points in screening with 2 level factorial designs to construct an estimate of error with n_c -1 and to observe effect of non linearity in the region of exploration Figure 1.

For further observation to obtain more information in extended observation region the CCD will used as the design of experiment, which easily augmented from the 2 level factorial design with the stars points Figure 2.

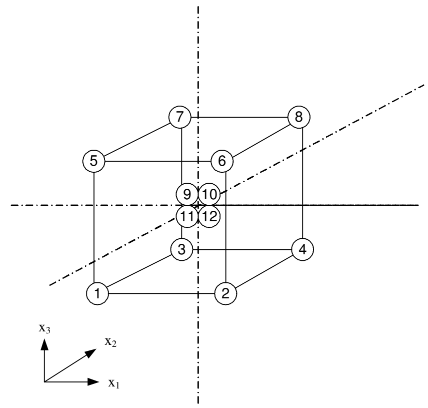

Figure 1 The 2 level factorial design augmented with 4 center points.

In order to estimate the pure experimental uncertainty of CCD, it is important to measure repeatedly the response function to the conditions determined by the central point. The number of such repeated measurements affects the determination of the position of the "axial star points" within the factor space.

Furthermore, to construct the CCD within three factor space, the number of experiments to be repeated in central point N_0 must be selected. For 2 level factorial design N_c (factor points) = 2^f = 8 and Na (axial star points) = 2 f = 6 positions, the distance of axial star points from the center points α is calculated according to the formula: [9]

$$\alpha^2 = \frac{\sqrt{(N_c + N_a + N_0)N_c} \quad N_c}{2} \quad (7)$$

for N_0 was chosen as 4 giving α = 1.414214 for rotatable design.

3.2 Coding of the Independent Variables

The variables were coded by taking into account the capacity and limiting cutting conditions of the milling machine. Using the following transforming equation:

$$x = \frac{\ln x_n \quad \ln x_{n0}}{\ln x_{n1} \quad \ln x_{n0}} \quad (8)$$

where x is the coded value of any factor corresponding to its natural value x_n, x_{n1} is the natural value of factor at the +1 level and x_{n0} is the natural value of the factor corresponding to the base or zero level [7], the level of the independent variables and coding identification are illustrated in Table 1.

Table 1. Process variables and their level

Independent Variable	Level in coded form				
	-α	-1	0	+1	+α
V $m.min^{-1}$ (x_1)	123.79	130.00	144.22	160.00	166.21
f_z $mm.tooth^{-1}$ (x_2)	0.0217	0.03	0.046	0.07	0.078
γ_o (°) (x_3)	5.76	7	9.54	13	14.24

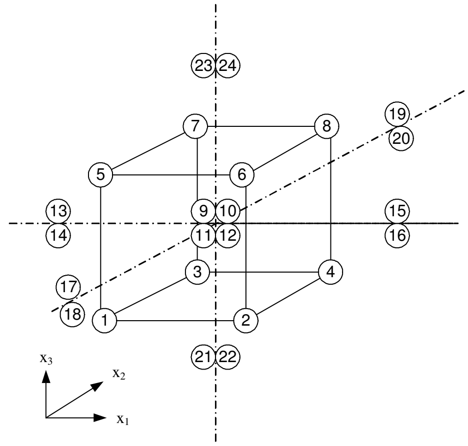

Figure 2 The proposed CCD used in observation.

3.3 Experimentation

A CNC MAHO 700S milling machine was used for side milling operation, which was carried out with a constant a_a (axial depth of cut) 5 mm and a_p (radial depth of cut) 2 mm under flood conditions with 6% of concentration water base coolant. The cutting tools used for experimentation, was solid carbide end mill cutters grade K30 with different radial rake angle according to the design of experiment.

The reference workpiece material was rectangular bar (110 x 110 mm) of Ti-6Al-4V and tool life criterions used were VB $\geq$ 0.25 mm, chipping and catastrophic failure.

The experiments was conducted sequentially from screening using 3F1 design augmented with 4 center points followed with CCD design with 1 replication for each star points. The analysis for CCD was carried out using Design Expert 6.0 package for both linear and quadratic CCD design.

4. RESULTS AND DISCUSSIONS

4.1 Development First Order Model Using 3F1 Factorial Design

The important components of the analysis and results are presented in figure form for further analysis. Cutting conditions and tool life results, shown in Table 2 is presented in coded variable to recognize the factorial and the center run.

In Figure 3, the contour of standard error design involved the curvature components as predicted in screening design. Even in Figure 4 show that only the three main factors have the significant influence on the machining condition. (A for Cutting Speed, B for feed rate fz and C for radial rake angle). The effect of curvature can also be recognized when 3F1 with center run design compared with pure linear CCD design.

For validation of the first order model using 3F1 with 4 center points, the ANOVA shown in Figure 5 is required. In this figured table is clearly to see that some effect of curvature is involved in the developed regression equation.

Table 2 Cutting conditions in coded factors and tool life results

Std	Run	Type	V	fz	RA	TL
			m.min	mm/tooth	deg	
1	7	Fact	-1	-1	-1	19.44
2	12	Fact	1	-1	-1	12.32
3	2	Fact	-1	1	-1	2.8
4	5	Fact	1	1	-1	1.29
5	4	Fact	-1	-1	1	7.41
6	8	Fact	1	-1	1	2.44
7	10	Fact	-1	1	1	0.56
8	11	Fact	1	1	1	0.31
9	9	Center	0	0	0	4.47
10	6	Center	0	0	0	5.47
11	1	Center	0	0	0	4.41
12	3	Center	0	0	0	5.93

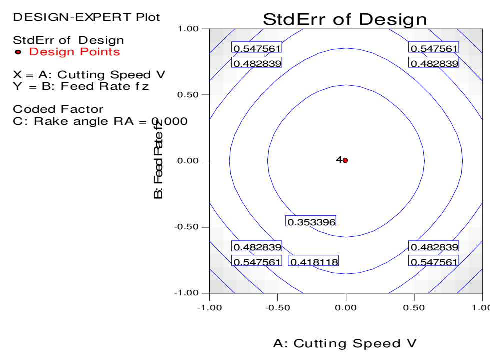

Figure 3 Contour of standard error design for 3F1-factorial model.

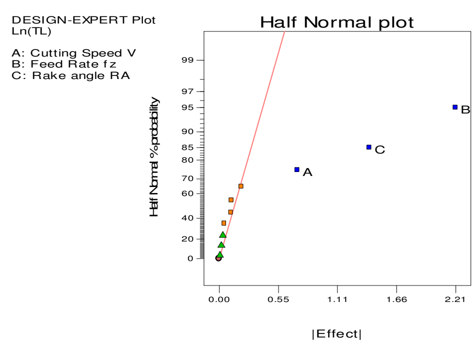

Figure 4 Main effects occurred

As shown in Figure 5, that lack of fit as a result from the sum of squares total subtracted with pure error occurred in replicated tests is not significant. This means that the developed equations can fit the tool life test result with accepted confidence level $\alpha = 0.05$, which is a standard confidence level commonly that is used for validating data population. This is also strengthened by Box-Cox analysis in Figure 6, which presented relative good result in confidence interval, because the analyzed line is almost in the middle between the low confidence individual (Low C.I.) and high confidence individual (High C.I).

Response: TL Transform: Natural log Constant: 0.000000

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	14.7906	3	4.93021	163.197	< 0.0001	significant
A	*1.07552*	*1*	*1.07552*	*35.6011*	*0.000560623*	
B	*9.76848*	*1*	*9.76848*	*323.350*	*< 0.0001*	
C	*3.94663*	*1*	*3.94663*	*130.639*	*< 0.0001*	
Curvature	1.04771	1	1.04771	34.6807	0.000606159	significant
Residual	0.211472	7	0.0302103			
Lack of Fit	*0.146110*	*4*	*0.0365274*	*1.67654*	*0.349920*	*not significant*
Pure Error	*0.0653621*	*3*	*0.0217874*			
Cor Total	16.0498	11				

Figure 5 ANOVA resulted in 3F1-model with 4 n_c.

From the analysis using Design Expert software with Ln transformation, the developed 3F1 tool life model in coded factor is

$$\hat{y} = 0.9883-0.3667x_1-1.10502x_2-0.70237x_3 \quad (9)$$

Equation (9) can be transformed by using equation (8) to provide the predictive tool life (min) as

$$\check{T} = 2.687915\, V^{-0.3667}\, fz^{1.10502}\, \gamma^{0.70237} \quad (10)$$

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

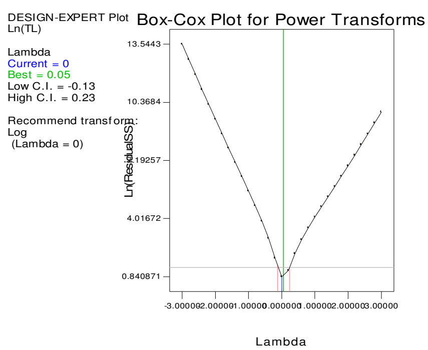

Figure 6 Box-Cox curve of 3F1-factorial model

This equation is valid for the side milling of titanium alloy Ti-6Al-4V using solid carbide under flood conditions with the following ranges of cutting speed V, feed per tooth fz and radial rake angle γ: $130 \le V \le 160$ m min^{-1}; $0.03 \le fz \le 0.07$ mm tooth^{-1}; and $7 \le \gamma \le 13$ (^{0}).

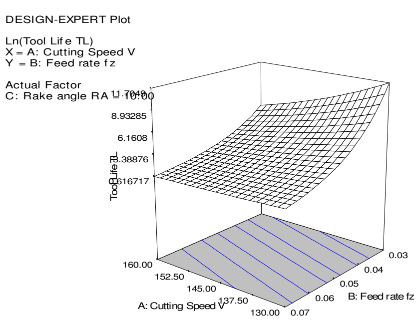

Figure 7 Response Surface of 3F1-model

The response of the 3F1 design in Figure 7 shown that, slightly curve occurred in the response region. According to this response surface, some possible solution of this model is presented in Figure 8.

Cutting Speed	is in range	130	160	1	1	3
Feed rate fz	is in range	0.03	0.07	1	1	3
Rake angle RA	is in range	7	13	1	1	3
Tool Life TL	is in range	5.00001	19.4399	1	1	3

Solutions

Number	Cutting Speed	Feed rate fz	Rake angle RA	Tool Life TL	Desirability	
1	143.29	0.05	7.43	5.46431	1.000	Selected
2	140.87	0.05	7.21	5.85521	1.000	
3	131.05	0.04	9.77	5.96418	1.000	
4	141.31	0.03	11.12	6.56315	1.000	
5	134.21	0.04	9.68	5.14965	1.000	
6	150.84	0.03	7.74	9.21434	1.000	
7	151.00	0.03	7.26	10.5127	1.000	
8	133.98	0.04	9.20	6.89768	1.000	
9	153.32	0.03	9.55	6.151	1.000	
10	142.26	0.03	10.02	7.46128	1.000	
11	143.63	0.05	7.29	6.08386	1.000	
12	141.68	0.05	8.76	5.03914	1.000	
13	153.01	0.05	7.07	5.37995	1.000	
14	144.69	0.05	8.49	5.04113	1.000	
15	133.69	0.04	9.56	6.67562	1.000	

Figure 8 Possible solution of the 3F1-model

4.2 Development of the model using the CCD design

Further investigation on the model for higher order was carried out using the CCD, which achieved with augmentation of 3F1-factorial design with additional replicated star points (shown in Figure 2).

Using the data from Table 3, the analyzing of CCD was began with the analyzing of fit summary as shown in Figure 9, two CCD model was suggested as significant. They are linear and quadratic model.

For this purpose, the higher order was selected backward to the linear model to avoid the unexpected sum of squares error. This method is more robust than forward or stepwise modeling otherwise selected the model manually.

The second order model resulted by the analysis in coded variables is given below,

$$\hat{y} = 1.7481-0.7194x_1-1.2799x_2-0.3627x_3-0.4854x_1^2 -0.3481x_2^2 \quad (11)$$

Table 3 Cutting conditions in coded factors and tool life results for CCD design

Std	Run	Type	V mm/min	fz mm/tooth	RA deg.	TL min
1	7	Fact	-1	-1	-1	19.44
2	12	Fact	1	-1	-1	12.32
3	2	Fact	-1	1	-1	2.8
4	5	Fact	1	1	-1	1.29
5	4	Fact	-1	-1	1	7.41
6	8	Fact	1	-1	1	2.44
7	10	Fact	-1	1	1	0.56
8	11	Fact	1	1	1	0.31
9	9	Center	0	0	0	4.47
10	6	Center	0	0	0	5.47
11	1	Center	0	0	0	4.41
12	3	Center	0	0	0	5.93
13	15	Axial	-1.4142	0	0	9.11
14	22	Axial	-1.4142	0	0	9.3
15	23	Axial	1.41421	0	0	0.41
16	21	Axial	1.41421	0	0	0.48
17	24	Axial	0	-1.4142	0	20.54
18	19	Axial	0	-1.4142	0	21.08
19	16	Axial	0	1.4142	0	0.33
20	18	Axial	0	1.4142	0	0.35
21	14	Axial	0	0	-1.4142	6.62
22	13	Axial	0	0	-1.4142	6.94
23	20	Axial	0	0	1.41421	6.46
24	17	Axial	0	0	1.41421	6.24

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

*** WARNING: The Cubic Model is Aliased! ***

Sequential Model Sum of Squares

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Mean	34.12	1	34.12			
Block	5.720E-004	1	5.720E-004			
Linear	36.60	3	12.20	26.83	< 0.0001	Suggested
2FI	0.058	3	0.019	0.036	0.9904	
Quadratic	4.08	3	1.36	3.94	0.0336	Suggested
Cubic	4.41	4	1.10	121.42	< 0.0001	Aliased
Residual	0.082	9	9.087E-003			
Total	79.36	24	3.31			

Figure 9 Fit summary of the second order CCD design.

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	0.000572040	1	0.000572040			
Model	40.4514	5	8.09028	28.7648	< 0.0001	significant
A	*8.28062*	*1*	*8.28062*	*29.4415*	*< 0.0001*	
B	*26.2091*	*1*	*26.2091*	*93.1860*	*< 0.0001*	
C	*2.10537*	*1*	*2.10537*	*7.48559*	*0.0140754*	
A^2	*3.01602*	*1*	*3.01602*	*10.7234*	*0.00446784*	
B^2	*1.55116*	*1*	*1.55116*	*5.51510*	*0.0312086*	
Residual	4.78135	17	0.281256			
Lack of Fit	*4.69957*	*8*	*0.587447*	*64.6486*	*< 0.0001*	*significant*
Pure Error	*0.0817809*	*9*	*0.00908677*			
Cor Total	45.2333	23				

Figure 10 ANOVA for CCD with quadratic model

From the ANOVA result, shown in **Figure 10**, it is obvious that the lack of fit of the proposed model is significant. Furthermore, from the Box-Cox analysis illustrated in Figure 11 that the need of transformation is also significant, because λ value did not include the λ = 1. However, further information given in this figure is that the model line falls in between confidence level LCI and HCI. This means, although the lack of fit is significant, the model could be used with reduced precision (slightly under confidence level α = 0.05.

Response surface as the result of predicted second order model is illustrated in Figure 12 shows that at the higher cutting speed the surface is approximately followed similar trend with the response of the 3F1-factorial design model in Figure 7. However, at lower cutting speeds the direction of the curve changes to achieve the maximum value, which follows the typical path of quadratic function when achieving the maximum value. This may cause failure when using the second order CCD design model. In this region the use of this model is not recommended.

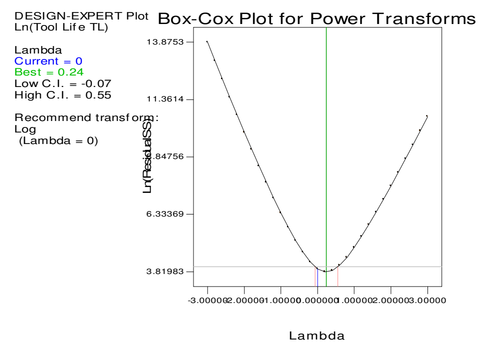

Figure 11 Box-Cox analysis for second order model

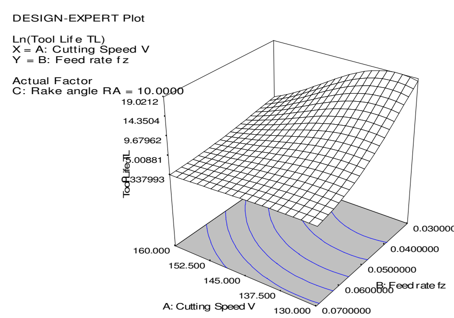

Figure 12 Response Surface of CCD quadratic design model.

4.3 Development of the First Order Model of CCD Design.

As illustrated in Figure 9, the second option of the model development suggested is the linear CCD model. To develop this model the factorial data from Table 3 which is identical with the data from Table 2 was used. This approach was made to avoid the accumulative error when too many unused data were taken into account while computing the analysis.

Response: TL Transform: Natural log Constant: 0.000000

*** WARNING: The Quadratic Model is Aliased! ***

*** WARNING: The Cubic Model is Aliased! ***

Sequential Model Sum of Squares

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Mean	17.2014	1	17.2014			
Linear	14.7906	3	4.93021	31.3232	< 0.0001	Suggested
2FI	0.0582587	3	0.0194196	0.0808525	0.967605	
Quadratic	1.04771	1	1.04771	27.3531	0.00638362	Aliased
Cubic	0.0878510	1	0.0878510	4.03220	0.138246	Aliased
Residual	0.0653621	3	0.0217874			
Total	33.2512	12	2.77093			

Figure 13 Fit and summary test for the first order CCD design model

The same steps in developing the second order CCD design modeling were done and delivered fit of summary for CCD design using factorials and center runs data in Figure 13. It is obvious to recognize that only the linear approach for CCD design model was suggested.

The first order model resulted from the CCD analysis in coded variables is given below,

$$\hat{y} = 1.1973 - 0.36667x_1 - 1.10502x_2 - 0.70247x_3 \quad \textbf{(12)}$$

Equation (12) can be transformed using equation (8) to provide the predictive tool life (min) as

$$\check{T} = 3.3127\, V^{-0.3667}\, fz^{1.10502}\, \gamma^{0.70237} \quad (13)$$

where Ť is the predicted tool life (min).

Use your mouse to right click on individual cells for definitions.

Response: TL Transform: Natural log Constant: 0.000000

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	14.7906	3	4.93021	31.3232	< 0.0001	significant
A	1.07552	1	1.07552	6.83312	0.0309363	
B	9.76848	1	9.76848	62.0623	< 0.0001	
C	3.94663	1	3.94663	25.0742	0.00104312	
Residual	1.25918	8	0.157398			
Lack of Fit	1.19382	5	0.238764	10.9588	0.0382961	significant
Pure Error	0.0653621	3	0.0217874			
Cor Total	16.0498	11				

Figure 14 ANOVA for CCD with linear model

Comparing ANOVA output resulted in 3F1 model Figure 5 with which resulted in a linear CCD Figure 14, it is easily recognized that the only one difference between both of them is, when in 3F1-ANOVA the effect of curvature was taken into account which was not the case in linear CCD-ANOVA. This effect is clearly seen in the developed model resulted from both analyses, the difference from each other is merely on their intercepts. It means the surface produced by linear CCD has a certain offset to the 3F1-model surface, but having the same form of curvature as shown in Figure 15 and Figure 7 respectively.

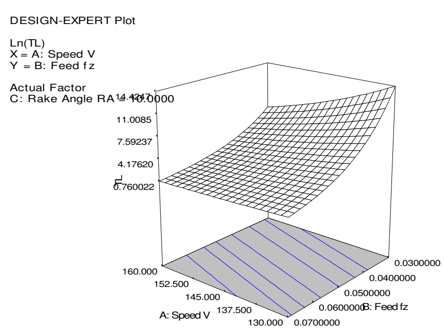

Figure 15 Response Surface of CCD linear model.

5. CONCLUSIONS

(1)The 3F1-model produced better results than linear CCD model because the effect of curvature was not taken into consideration by the linear CCD.

(2)An Additional effect of the curvature provides a certain offset to linear CCD model when compared to 3F1-model.

(3)Main effect of the rake angle in first order model decreases in the second order model. It can be recognized when the extreme value of rake angle points 21 – 24 resulted in almost the same tool life values.

(4)The RSM was found to be very useful in the development mathematical models and optimizing the machining response when end milling titanium.

(5)Based on the graphical results, it was found that in order to achieve higher tool life (above 5 minutes), the cutting conditions should be maintain at medium range (V: 130-153 m min^{-1}, fz: 0.03-0.05 mm $tooth^{-1}$, radial rake angle γ: 7-10^0) for all the parameters investigated Figure 8.

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