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Papers

Cutting Force Predictions Models in End Milling Titanium Alloy Ti-6Al-4V

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Abstract

This paper presents a study of the development of predicted mathematical models for average tangential cutting force in end milling titanium alloy Ti-6Al-4V using uncoated solid carbide tools under flood conditions. In developing the cutting force models, the primary machining parameters such as cutting speed, feed and radial rake angle, were used as independent variables for factorial design of experiment coupled with response surface methodology (RSM). Results from the 3D-response surface contour showed that an almost constant level of cutting force was obtained during machining this advanced material. An optimum cutting conditions was also identified for a particular range of cutting force values. The models were tested by analysis of variances and were found to be adequate.

Keywords: Cutting force, End milling, Titanium Alloys, Factorial design, RSM.

1 Introduction

Titanium and its alloys are used extensively in the aerospace industry for turbine and compressor blades in the cooler parts of the engine. They are known to have excellent strength to weight ratios and corrosion resistance coupled with good elevated temperatures properties and an oxidation limit of ~ 600 °C. The α-β alloy, Ti-6Al-4V is the most common and accounts for over half of the world's sales of titanium alloys.

Numerous studies have shown titanium and its alloys are difficult to machine, regardless of the various types of cutting tools 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 all cutting tool materials.

Although the cutting forces generated are not excessively high (almost similar to those with steel), they are confined to a small area due to the short chip contact length which leads to high stresses. The combination of high stress and temperature resulted in plastic deformation of the tool edge. Depth of cut notching and chipping at the flank can also be a problem with intermittent cutting operations. [1]

End milling is one of the most widely used machining operation and the aerospace industry places heavy demand on this process due to both the shape and complexity of the parts and the dimensional accuracy required. Recent approaches to the problem of designing a suitable data selection system for Computer Integrated Manufacturing (CIM) application are to use machinability database systems in the form of mathematical model which have considerable advantages over simple data retrieval systems [2]. For this purpose, an approach to develop a mathematical model for the average tangential cutting force in end milling Ti-6Al-4V by factorial design of experiment coupled with RSM was conducted.

2 Cutting Forces in End Milling

The basic geometry of the end milling process for down milling is presented in Figure 1. The cutting force components acting on one tooth of the end mill cutter are shown in Figure 2. There are two cutting force components system. The first is the table system (F_x, F_y, F_z, F_R), its indices illustrated the direction of the cutting force in x-y-z coordinate respectively and the resultant force. The second is known as the cutter system of cutting forces which consists of four components F_t, F_r, F_a and F_R', they are tangential, radial, axial and projection of the resultant force respectively [3][4].

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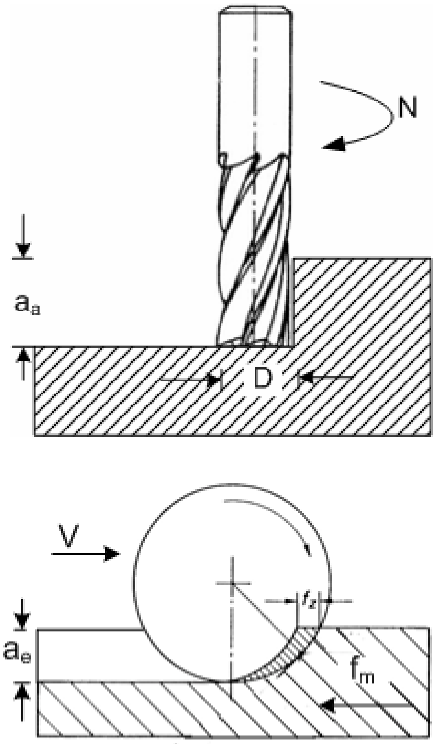

Figure 1 Basic Geometry of an End Milling Process (Down Milling)

2.1 Average Cutting Force in multi-tooth End Milling

The average cutting force is very useful for engineers in designing machine tools and in setting up the cutting system, although it is not the maximum cutting force occurred in an end milling process. If several teeth are cutting simultaneously, then the total average cutting forces acting on the teeth of the cutter per cut in table system are

$$F_{XT} = \sum_{i=1}^{z_c} \delta(i).F_{xi}(\Psi_i) \quad (1)$$

$$F_{YT} = \sum_{i=1}^{z_c} \delta(i).F_{yi}(\Psi_i) \quad (2)$$

$$F_{ZT} = \sum_{i=1}^{z_c} \delta(i).F_{zi}(\Psi_i) \quad (3)$$

where

$$\delta(i) = 1 \quad if \ \Psi_1 \leq \Psi \leq \Psi_2$$
$$= 0 \quad otherwise$$

F_{XT}, F_{YT} and F_{ZT} are the total average cutting forces acting on the teeth of the cutter per cut in the X, Y, and Z direction respectively, and F_x, F_y and F_z are the instantaneous cutting force on an individual tooth per cut in X, Y and Z direction respectively while Ψ_i is the instantaneous angle of the cutter.

For a multi tooth milling cutter of uniform pitch the average cutting force components in table system per tooth are

$$F_{xa} = \frac{F_{XT}}{z_c} \quad (4)$$

$$F_{ya} = \frac{F_{YT}}{z_c} \quad (5)$$

$$F_{za} = \frac{F_{ZT}}{z_c} \quad (6)$$

where z_c is the number of teeth cutting simultaneously, z_c is not being rounded off to the nearest whole number and it can be determined as

$$z_c = \frac{z \ x \ \Psi_s}{360} \quad (7)$$

in which z is the number of teeth in the cutter and Ψ_s is the swept angle $(\Psi_2 - \Psi_1)$, which can be determined in term of cutting parameters [3][4].

In cutter system for a multi-tooth milling process, the average tangential force F_{ta} per tooth and average radial force per tooth F_{ra} are

$$F_{ta} = F_t \ x \ z_c \quad (8)$$

$$F_{ra} = F_r \ x \ z_c \quad (9)$$

where F_t and F_r are the instantaneous tangential and radial forces acting per tooth of the cutter per cut.

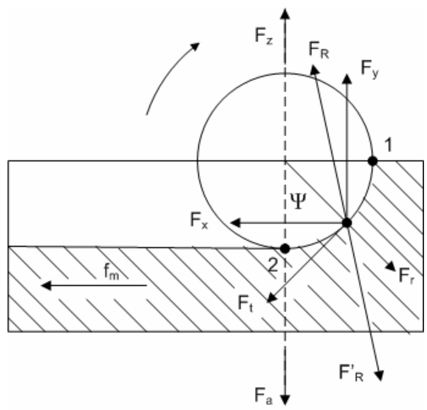

Figure 2 Cutting Force Components Acting onOne Tooth of an End Mill Cutter (Down Milling).

2.2 Table and Cutter System Relationship of Cutting Force

Figure 2 shows that the average resultant cutting force acting on the workpiece in table system F_{Ra} can be determined as

$$F_{Ra} = \sqrt{F_{xa}^2 + F_{ya}^2 + F_{za}^2} \quad (10)$$

The average resultant cutting force acting on the cutter in the cutter system F_{Ra}' can be formulated as

$$F_{Ra}' = \sqrt{F_{ta}^2 + F_{ra}^2 + F_{aa}^2} \quad (11)$$

For static equilibrium it is assumed that F_R = F_R' (or F_{Ra} = F_{Ra}') and when the cutter is mounted correctly, the cutter axis and the spindle axis coincide each other, then it is commonly assumed that $F_z = F_a$ (or $F_{za} = F_{aa}$).

Assuming that a plane system exist, it is possible to relate the forces on the milling table to those on the cutter for down milling process as

$$F_{ta} = F_y \sin(\Psi_i) - F_x \cos(\Psi_i)$$
$$F_{ra} = F_y \cos(\Psi_i) + F_x \sin(\Psi_i) \quad (12)$$

3 Development the Mathematical Model for Cutting Forces

In machinability study investigations, statistical design of experiment is used quite extensively. Statistical design of experiment refers to the process of planning the experiment so that the appropriate data can be analyzed by statistical methods, resulting in valid and objective conclusions. Design and method such as factorial design of experiment and RSM are nowadays widely used to replace one-factor-at-a-time experimental approach which is time and cost consuming.[5]

For this purpose, the mathematical model relating to the machining response and their factor were developed to facilitate the optimization of the machining process. They have been developed stepwise using 3F1-factorial design and RSM using experimental results.

3.1 Postulation of the Mathematical Models

It is assumed that the proposed model for the cutting force is merely a function of cutting speed V, feed f_z and radial rake angle γ. Other factors such as machine tools stability, entry and exit condition etc are kept constant. Thus the proposed models for cutting force in end milling Ti-6Al-4V can be expressed as

$$F_{ta} = CV^k f_z^l \gamma^m \varepsilon' \qquad (13)$$

where F_{ta} is the calculated average tangential cutting force (N), f_z is the feed per tooth (mm.tooth^{-1}), γ is the radial rake angle (^{o}), ε' is the experimental error and C, k, l, m are parameters to be estimated using experimental data.

By performing a natural logarithmic transformation equation 13 can be converted into first order polynomial as

$$\ln F_{ta} = \ln C + k \ln V + l \ln f_z + m \ln \gamma + \ln \varepsilon' \qquad (14)$$

which can also be formed as

$$y = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + \varepsilon \qquad (15)$$

and finally can be written as

$$\hat{y}_1 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \qquad (16)$$

where y is the calculated average tangential force on a natural logarithmic scale, $\hat{y}_1$ is the natural logarithmic value of predictive (estimated) tangential cutting force, $x_0 = 1$ (a dummy variable), x_1, x_2 and x_3 are the coded variables of V, f_z, and γ respectively, $\varepsilon = \ln \varepsilon'$ and b_0, b_1, b_2 and b_3 are the model parameters to be estimated using the experimental data. [6]

In extended observation region, the second-order model is also useful when the second order effect of V, f_z, γ and the two way interactions amongst V, f_z, and γ are significant. The second order can be extended from the first-order model in equation 16 as

$$\begin{aligned} \hat{y}_2 &= y - \varepsilon \\ &= b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \\ &\quad + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \\ &\quad + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 \end{aligned} \qquad (17)$$

where the b values are the parameters, which are to be estimated by method of least squares and $\hat{y}_2$ is the estimated response on logarithmic scale.

Validity of the models used for optimizing the process parameters has to be tested using ANOVA.

3.2 Experimental Works

Before commencing the experimental trials, thorough planning was essential in order to obtain the relevant data in developing the mathematical models. By taking into consideration the factors for experimentation and analysis such as cutting speed, feed and radial rake angle, the design of experiments (DOE) were used stepwise from 2^3-factorial design to central composite design (CCD), which is easily gained by augmentation 2^3-design with replicated star points.

3.2.1 Experimental Design

In this study, the 2^3-factorial design shown in Figure 3, was used as screening trials of the experiments. This is one of which all levels of a given factor are combined with all levels of every other factor in the experiment. This design is necessary when interactions between variables are to be investigated. Furthermore, factorial design allow the effects of a factor to be estimated at several levels of other factors, giving conclusions that are valid over a range of experimental conditions [7][8].

To observe the effect of non linearity in the region and to construct an estimate of error with n_c - 1, it is useful to use additional center points in screening with 2 level factorial designs when the factorial points in the designs are not replicated [6][8].

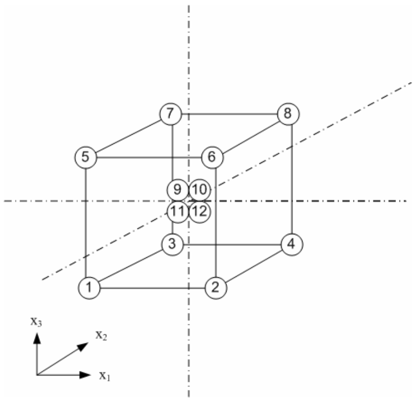

Figure 3 3F1-Factorial Design Augmented with 4 Center Points and First-Order CCD for k = 3.

An extended design of 2^3-design is a second order CCD design, which is augmented with replicated star points as shown in Figure 4. The numbers of such repeated measurements affect the distance of the "axial star points" within the factor space. According to previous study [6] the distance of axial star points to the center points α is 1.4142.

3.2.2 Coding of the Independent Variables

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

$$x = \frac{\ln x_n - \ln x_{n0}}{\ln x_{nl} - \ln x_{n0}} \qquad (18)$$

where x is the coded variable of any factor corresponding to its natural x_n, x_{nl} 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 [2][3][6][7]. The level of the independent variables and coding identification are illustrated in Table 1.

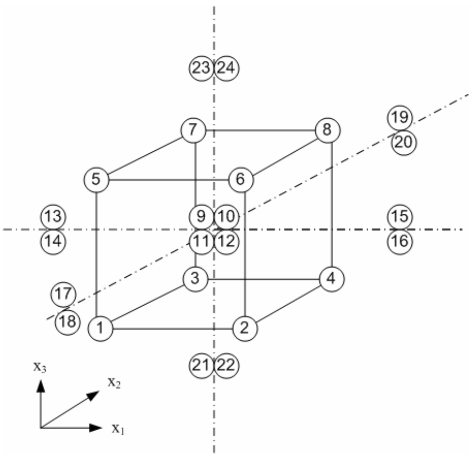

Figure 4 Second Order CCD for k = 3.

Table 1 Levels of Independent Variables for Ti-6Al-4V

Independent Variable	**Level in coded form**				
	-α	-1	0	+1	+α
V ($m.mm^{-1}$) x_1	124.53	130.00	144.22	160.00	167.03
f_z ($mm.tooth^{-1}$) x_2	0.025	0.03	0.046	0.07	0.083
γ (°) x_3	6.2	7.0	9.5	13.0	14.8

3.2.3 Experimental Set-Up

For the experimentation, a CNC MHO 700S milling machine was used for side milling process, which was 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. The grade-K30 solid carbide end mill cutter with different radial rake angle according to design of experiment, were used in the experiments.

The cutting forces were measured at the first cut of the whole cutting process of each end mill cutter using multi component force measuring system consisting of the following elements:

- A 3-component dynamometer comprising of basic unit (Kistler, Type 9265B) and a screwed-on working adapter for milling (Kistler, Type 9443B).
- A multi channel charge amplifier (Kistler, Type 5019A).
- A data acquisition system consisting of a personal computer (PC) equipped with an A/D board as well as the DynoWare software (Kistler, Type 2825 D1-2, version 2.31).

The reference workpiece material of Ti6Al-4V was a rectangular block of 110 mm x 110 mm x 400 mm and the analysis for the developed models were carried out using a Design Expert 6.0 package.

4 Experimental Results and Discussion

4.1 The 3F1-Model of the Cutting Force

Using the experimental results in Table 2, the cutting force prediction model can be formulated as

$$\hat{y} = 4.237 - 0.01052x_1 + 0.3123x_2 - 0.0546x_3 + 0.02611x_1x_3 - 0.03472x_2x_3 \quad (19)$$

This equation shows that the cutting force decreases with increasing cutting speed and radial rake angle, and in contrary it increases with increase in feed. From the interaction terms, it was observed that the combination of speed and radial rake angle contributes to the increase in cutting force. However the combination of feed and radial rake angle adversely reduces the cutting force, whilst the feed alone tends to increase in cutting force. The response surface of the cutting force distribution in relation to cutting speed and rake angle is shown graphically in Figure 5.

Table 2 Experimental Results for 3F1-Factorial and Linear CCD-Model with k = 3

Std	**Type**	**V**	**f_z**	**γ**	**Calculated Fc**
		$m.min^{-1}$	**mm/tooth**	**deg.**	**N**
1	Fact	-1	-1	-1	53.66
2	Fact	1	-1	-1	49.75
3	Fact	-1	1	-1	107.16
4	Fact	1	1	-1	99.83
5	Fact	-1	-1	1	48.87
6	Fact	1	-1	1	50.45
7	Fact	-1	1	1	85.20
8	Fact	1	1	1	87.84
9	Center	0	0	0	76.70
10	Center	0	0	0	74.84
11	Center	0	0	0	73.15
12	Center	0	0	0	79.99

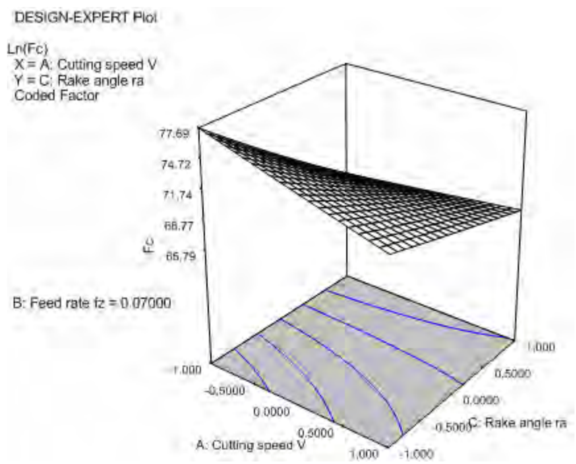

Figure 5 Response Surface for 3F1-Factorial Model

By using ANOVA, the validation of this equation is shown in Table 3. From he results, it is evident that the 3F1-model is valid for the observation region, because the lack of fit (LOF) of this model is not significant.

Table 3 ANOVA for 3F1-Factorial Model

Response: Fc Transform: Natural log Constant: 0.0000
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	0.8201	5	0.1640	204.6	< 0.0001	significant
A	*0.0008857*	*1*	*0.0008857*	*1.105*	*0.3413*	
B	*0.7803*	*1*	*0.7803*	*973.4*	*< 0.0001*	
C	*0.02385*	*1*	*0.02385*	*29.75*	*0.002816*	
AC	*0.005452*	*1*	*0.005452*	*6.801*	*0.04779*	
BC	*0.009643*	*1*	*0.009643*	*12.03*	*0.01788*	
Curvature	0.02732	1	0.02732	34.08	0.002086	significant
Residual	0.004008	5	0.0008016			
Lack of Fit	*6.192E-006*	*2*	*3.096E-006*	*0.002321*	*0.9977*	*not significant*
Pure Error	*0.004002*	*3*	*0.001334*			
Cor Total	0.8515	11				

4.2 The First-Order CCD-Model

The same data in Table 2 was used for developing the first order CCD-model. The first order model for cutting force is

$$\hat{y} = 4.271 - 0.01052x_1 + 0.3123x_2 - 0.05460x_3 \qquad (20)$$

Equation 20 can be presented in the following form:

$$F_c = 1711.6736V^{-0.10133} f_z^{0.73717} \gamma^{-0.1764} \qquad (21)$$

The results generated from equations 19 and 20 showed that they have the same coefficient in the linear region. The difference between both equations in the linear region is merely on their intercepts, i.e 4.237 and 4.271 for 3F1 model and linear CCD model respectively. It means that same effect are obtained from both equations in the observation region, however the 3F1-factorial model provides more information about the intersection effect between the cutting speeds combined with radial rake angle and between the feed combined with radial rake angle.

More information resulted in CCD linear model is shown by the response surface in Figure 6. From this figure it can be recognized that with increasing cutting speed, the cutting force decreases very slightly. Similar finding was reported by other researchers [9][10] for the observation region of cutting speed.

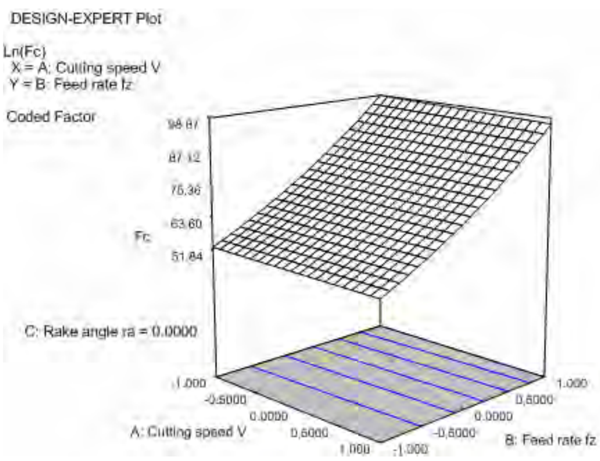

Figure 6 Response Surface for Linear CCD-Model

For validation of the linear CCD-model, ANOVA was used and the results are shown in Table 4. It shows that the LOF of the first order CCD model is not significant, thus the model can be accepted within the observation region.

Table 4 ANOVA for the First Order CCD-Model

Response: Fc Transform: Natural log Constant: 0.0000
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	0.8050	3	0.2683	46.24	< 0.0001	significant
A	*0.0008857*	*1*	*0.0008857*	*0.1526*	*0.7062*	
B	*0.7803*	*1*	*0.7803*	*134.5*	*< 0.0001*	
C	*0.02385*	*1*	*0.02385*	*4.110*	*0.07718*	
Residual	0.04643	8	0.005803			
Lack of Fit	*0.04242*	*5*	*0.008485*	*6.361*	*0.07937*	*not significant*
Pure Error	*0.004002*	*3*	*0.001334*			
Cor Total	0.8515	11				

4.3 The Second-Order CCD-Model

A second-order model was postulated to extend the variables range in obtaining the relationship between the cutting force and the machining variables. The model is based on the second order CCD for k=3 (Figure 4) and 24 set of experiments given in Table 5. The result is presented in the following form:

$$\begin{aligned}\hat{y} &= 4.35 + 0.008803x_1 + 0.2587x_2 - 0.09927x_3 \\ &- 0.02905x_1^2 - 0.05502x_2^2 - 0.01716x_3^2 \\ &+ 0.0004374x_1x_2 + 0.02611x_1x_3 - 0.03472x_2x_3\end{aligned} \qquad (22)$$

Table 5 Experimental Results of the Second Order CCD-Model for k = 3

Std	Type	V	f_z	Γ	Calculated Fc
		$m.min^{-1}$	mm/tooth	Deg.	N
1	Fact	-1	-1	-1	53.66
2	Fact	1	-1	-1	49.75
3	Fact	-1	1	-1	107.16
4	Fact	1	1	-1	99.83
5	Fact	-1	-1	1	48.87
6	Fact	1	-1	1	50.45
7	Fact	-1	1	1	85.20
8	Fact	1	1	1	87.84
9	Center	0	0	0	76.70
10	Center	0	0	0	74.84
11	Center	0	0	0	73.15
12	Center	0	0	0	79.99
13	Axial	-1.4142	0	0	74.84
14	Axial	-1.4142	0	0	67.53
15	Axial	1.4142	0	0	68.56
16	Axial	1.4142	0	0	86.43
17	Axial	0	-1.4142	0	51.22
18	Axial	0	-1.4142	0	53.90
19	Axial	0	1.4142	0	100.82
20	Axial	0	1.4142	0	87.41
21	Axial	0	0	-1.4142	95.33
22	Axial	0	0	-1.4142	90.45
23	Axial	0	0	1.4142	55.69
24	Axial	0	0	1.4142	68.59

It was interesting to observe that when the region was extended, the contour of cutting force in the cutting speed range changes from linear (Figure 6) to a slightly curve form (Figure 7). This was also confirmed by other researchers [9][10] for low and high cutting speeds region. They found that the cutting force was very high at low cutting speed and reduced rapidly at medium cutting speed and finally increased slightly with further increase in cutting speed. It was also observed in Figure 7 that there was a significant increase in cutting force with increase in feed.

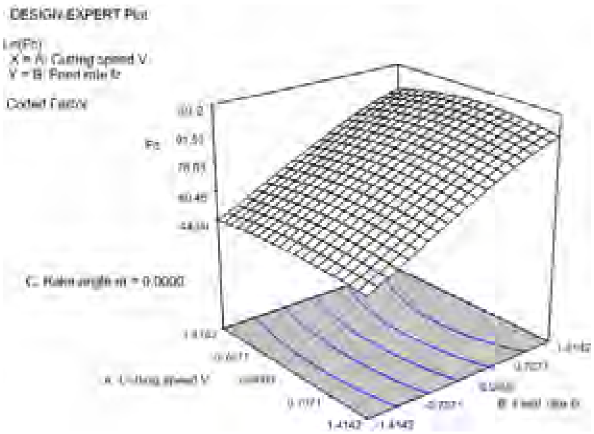

Figure 7 Response Surface for the Second Order CCD-Model

From ANOVA results, it was also found that the second order CCD model can be used as the mathematical model in the region of observation, since the LOF of this model is not significant as shown in Table 6.

Table 6 ANOVA for the Second Order CCD-Model

Response:	Fc	Transform:	Natural log	Constant:	0.0000	
ANOVA for Response Surface Quadratic Model						
Analysis of variance table [Partial sum of squares]						
Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Block	0.003271	1	0.003271			
Model	1.285	9	0.1427	12.01	< 0.0001	significant
A0.001240	*1*	*0.001240*	*0.1043*	*0.7518*		
B1.071	*1*	*1.071*	*90.14*	*< 0.0001*		
C0.1577	*1*	*0.1577*	*13.27*	*0.002980*		
A:0.01012	*1*	*0.01012*	*0.8520*	*0.3728*		
B:0.03632	*1*	*0.03632*	*3.057*	*0.1040*		
C:0.003532	*1*	*0.003532*	*0.2973*	*0.5948*		
AB1.531E-006	*1*	*1.531E-006*	*0.0001288*	*0.9911*		
AC0.005452	*1*	*0.005452*	*0.4588*	*0.5101*		
BC0.009643	*1*	*0.009643*	*0.8114*	*0.3841*		
Residual	0.1545	13	0.01188			
Lack of Fit	*0.08381*	*4*	*0.02095*	*2.668*	*0.1020*	*not significant*
Pure Error	*0.07068*	*9*	*0.007853*			
Cor Total	1.442	23				

5 Conclusions

- There are three appropriate prediction models namely 3F1-, linear CCD and second order CCD model to formulate the relationship amongst the machining parameters such as cutting speed (130-160 m/min), feed (0.03-0.07 mm/tooth), radial rake angle (7-13 ^{o}).
- With increasing cutting speed, the cutting force decreases slightly in the region of observation.
- Feed is the most significant factor that influences the cutting force. It increases significantly with increasing feed in the observation region.
- Increasing the radial rake angle gradually reduced the cutting force.

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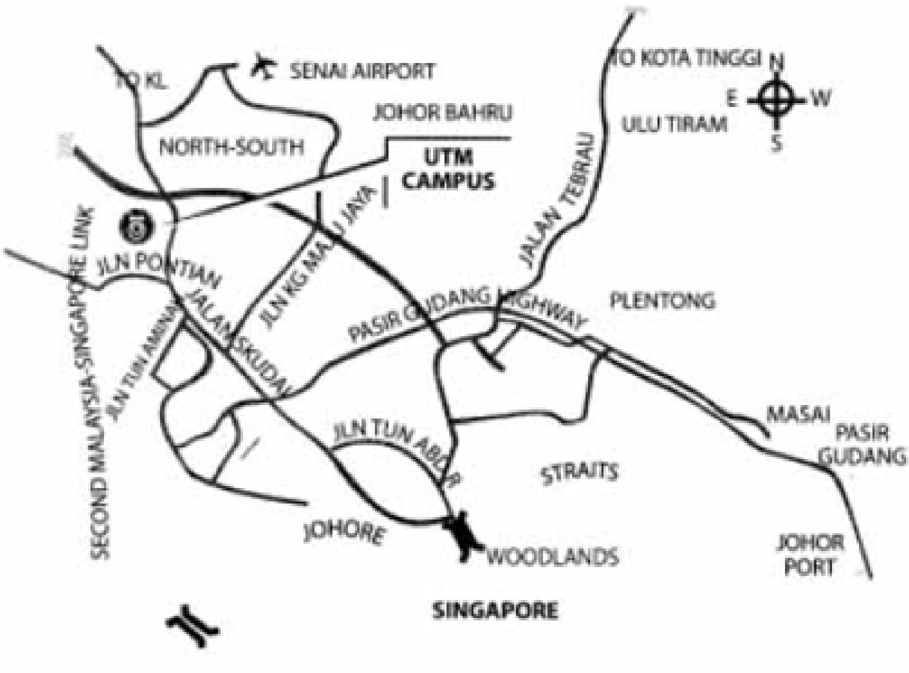
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