Inching Towards Science Based Research by 2020

ICOMAST 2006

International Conference On MANUFACTURING SCIENCE AND TECHNOLOGY

Melaka, Malaysia, August 28 – 30, 2006

Edited by

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and

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Faculty of Engineering and Technology,
Multimedia University,
Jalan Ayer Keroh Lama,
Bukit Beruang, 75450 Melaka, Malaysia.

ISBN 983-42051-2-0

Price: RM10 / US$4.00

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FOREWORD

Writing a foreword for the ICOMAST 2006 Proceedings is indeed a pleasure. ICOMAST 2006 is the 11th Conference I am involved in and most of the time as the main organizer. But this one is an exception as we have two distinguished guests at the opening ceremony: Datuk Seri Mohd. Ali Rustam, Chief Minister of Melaka and Tun Dr. Siti Hasmah Hj. Mohd Ali, Chancellor, Multimedia University

The 1st conference I organized was the 4th AIMTDR (All India Machine Tool Design and Research) at the Indian Institute of Technolgy, Madras where I started my career. The AIMTDR conferences were inspired by the annual MTDR Conferences in the UK held alternatively in Birmingham and Manchester under the late Professors Tobias and Koenigsberger. The subsequent ones I organised were while working in NUS, Singapore under CIRP-UNESCO auspices in 1982 and again in 1988 August prior to the CIRP General Assembly in Tokyo. The next two were in Cookeville TN, USA while working in Tennessee Technological University, the first was the CIRP Seminar and the second the 7th ICAPE (International Conference on Production Engineering) jointly with Professor McGeough. The next two were again in Singapore while working in Nanyang Technological University and these were the ICOPE conferences (International Conference On Production Engineering). While in NTU in Singapore I organised the 1st ICAMT (Conference on Advanced Manufacturing Technology) in UTM Johor Bahru. This was followed by 2nd and 3rd ICAMT when I moved to UTM. For eight of these conferences I brought out special edited issues with Elsevier's Journal of Materials Processing Technology. These 10 conferences showed me the power of citations and the impact factor which find their way into Google Web, Google Book Search, and Google Citations. The MTDR conferences in those days had an enormous citation and impact factor.

CIRP (College Internationale Recherche Production) is the French acronym for the International Academy for Production Engineering Research. The CIRP General Assemblies are held annually in one of its member countries and its papers are published annually in CIRP Annals which have an impact factor of 1. ICOMAST 2006 is privileged to have the CIRP President, Professor George Chryssolouris of the University of Patras, Greece, and formerly a MIT faculty, deliver the inaugural address. Other CIRP Fellows who will deliver keynotes are Professors McGeough (a Fellow of the Royal Society of Engineering, Edinburgh), Jawahir, Rahman, and Weckenmann. Yours truly who is a Fellow and two CIRP Associate Members are also with us, Dr. A. Srivastava of Tech-Solve, USA, and Dr. P. V. Brevern our Dean of FET. The 6th Keynote Speaker is one of India's top manufacturing specialists Professor V.K. Jain of the Indian Institute of Technology, Kanpur. To them I extend a cordial welcome and express my gratitude for their being here. Their presence and their papers will have an impact factor and garner many citations. May I also add that of the previous 10 conferences, the 7th ICAPE has brought many citations and these figures prominently in Google and incidentally my co-author was Professor McGeough who is with us today.

This conference bears all the hall marks of success. This is due to the great team work I had and I owe a deep debt of gratitude to our President Professor Datuk Dr. Ghauth Jasmon, our Dean Dr. P.V. Brevern, to A/Prof. Dr. Nabil El-Tayeb, Ms. Y. F. Law, Mr. B. F. Yousif, Mr. K. O. Low, and Mr. S. L. Beh.. My thanks to members of the technical team A/Prof. Dr. Maleque, Dr. Khaled, Dr. T. S. Lee, Dr. D. Rilling for helping in the review of papers. Thanks to the local hospitality committee from FET headed by Mr. S.L. Beh. Thanks to Ms. Om Karini (CU), Ms. Juanna, Ms. Noor Hamiza, and Mr. Bukhari whose help along with Mr. Beh in the opening ceremony is deeply appreciated.

Thanks in particular to Messrs Nabil, Low, and Yap for bringing out a fantastic Souvenir which highlights the ICOMAST 2006 programme, gives sketches of keynote speakers, contains photographs of all major volunteers and highlights the city of Melaka. I am thankful to organizations that took up advertisements in our souvenir for small and bigger amounts that finally add up to a big amount.

For running a conference of this magnitude, financial support is essential. I am thankful for the generous seed money given by our MMU President and to Dr. Hans Meyer CEO of Infineon (Malaysia) Technologies Sdn. Bhd. for a bountiful RM 20,000. My thanks to the Institution of Engineers (Malaysia) for their support.

I would like to thank three journals and their editors for kindly agreeing to accept carefully screened and refereed papers:

International Journal of Manufacturing Science and Management, Inderscience, UK

International Journal of Manufacturing Science and Technology, Advanced Solutions Inc., USA

Machining Science and Technology, Taylor and Francis, USA

Last but not least are the authors whom I thank sincerely for contributing good papers and for attending this conference.

Chairman, Organising Committee

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OPTIMIZATION OF SURFACE ROUGHNESS PREDICTION MODEL IN END MILLING TITANIUM ALLOY (Ti-6Al4V)

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ABSTRACT

This paper reports on the development of predicted mathematical models for surface roughness when end milling titanium alloy (Ti-6Al-4V) using uncoated solid carbide under flood conditions. Factorial design of experiment coupled with response surface methodology (RSM) were used in developing the surface roughness models in relation to the primary machining variables such as cutting speed, feed and radial rake angle. 3 D response surface contours were also constructed and used in determining the optimum cutting conditions for a particular range of surface roughness values. The adequacy of the predictive models was verified by ANOVA. Experimental results showed that lower surface roughness can be obtained by employing higher cutting speed, low feed rate and high radial rake angle value when end milling Ti-6Al4V.

Keywords: Surface roughness, End milling, Titanium Alloys, Response Surface Methodology (RSM)

1. INTRODUCTION

Increasing trend in using titanium alloy for airframe structures is mainly due to its high resistance to oxidation at elevated temperature and its low weight-to-strength ratio. However, due to poor machinability of titanium alloys, the selection of acceptable machining conditions is crucial.

Surface integrity such as surface roughness is very critical to the functionality of a machined components. It influences several functional attributes of a part, such as coefficient of friction, mating characteristics, fatigue, heat transfer etc. Thus measurement of surface finish represents one of the most important aspects in the analysis of machining process. Previous studies [1][2] have shown that the appropriate range of feeds and cutting speeds, which provide a satisfactory surface finish and tool life is very limited.

Although in the past, many studies [3][4][5] had been carried out to predict the surface roughness values during end milling operation in terms of the primary machining parameters, the effect of tool geometry was not taken into consideration.

Therefore, an effort has been made in this investigation to evaluate the influence of tool geometry (radial rake angle), cutting speed and feed rate when end milling Ti-6Al4V using solid carbide tool.

The aim of this study was to develop predicted mathematical models (first and second order) for surface roughness when end milling titanium alloy (Ti-6Al-4V) using uncoated solid carbide under flood conditions. Response surface methodology (RSM) was adopted [6] which is one of most useful tools for modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response.

2. DESCRIPTION OF MATHEMATICAL MODEL

The mathematical surface roughness model (response surface) in end milling in relation to the independent variables investigated can be expressed as

$$R_a = CV^k f_z^l \gamma_o^m \quad \textbf{(1)}$$

where R_a is the experimental (measured) surface roughness (μm), f_z is the feed per tooth (mm $tooth^{-1}$), γ_o is the radial rake angle (^{o}) and C, k, l, m are model parameters to be estimated using the experimental data.

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

$$ln\, R_a = ln\, C + k\, ln\, V + l\, ln\, f_z + m\, ln\, \gamma_o \quad \textbf{(2)}$$

The linear model of Eq. (2) is

$$y = \beta_o x_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \quad \textbf{(3)}$$

where y is the true response of surface roughness on a logarithmic scale x_o = 1 (dummy variable), x_1, x_2, x_3 are logarithmic transformation of cutting speed, feed and radial rake angle respectively, while β_o, β_1, β_2, β_3 are the parameters to be estimated. Eq. (3) can also be written as

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

where $\hat{y}_1$ is estimated response, ε the experimental error and the b_i values are estimates of the β_i parameters.

The second order model can be extended from the first order model's equation as

$$\hat{y}_2 = b_o x_o + b_1 x_1 + b_2 x_2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 + b_{11} x_1 x_1 + b_{22} x_2 x_2 + b_{33} x_3 x_3 \quad \textbf{(5)}$$

where $\hat{y}_2$ is the estimated response based on the second order equation. Validity of the selected model used for optimizing the process parameters has to be tested using ANOVA.

3. EXPERIMENTAL DETAILS

3.1 Experimental Design

The design of experiment has a major effect on the number of experiments needed. Therefore, it is essential to have a well-designed experiment so that the number of experiments required can be minimized. In this study, a 2 level factorial design using 3F1-factorial design was used as screening trials of the experiment to determine the significant factors. Since, the factorial points in the design are not replicated, it is useful to add 4 center points in screening trials. This enables the construction of an estimate of error with n_c-1 and to observe the effect of nonlinearity in the region of exploration[7].

In order to obtain more information in the extended observation region, the central composite design (CCD) was used as the design of experiment, which easily augmented from 3F1-factorial design with star points as presented in Fig. 1.

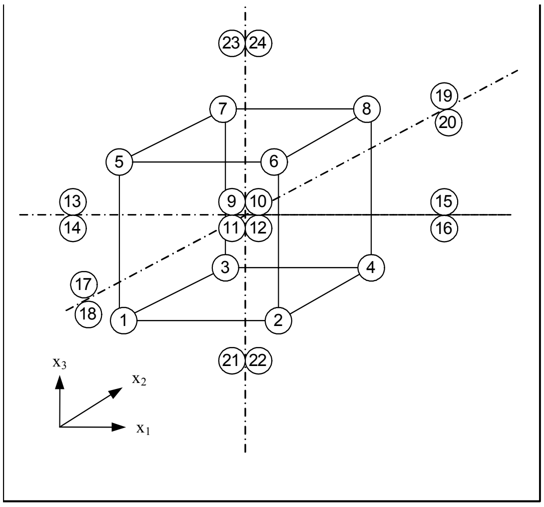

Fig. 1 The CCD design used in experiments

The distance between center points and star points α = 1.4142, which was calculated according to previous study [2] for $n_c = 4$ with 3 factors.

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 transformations

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

where x is the coded value of any factor corresponding to its natural value x_n. x_{nl} is the +1 level and x_{n0} is the natural value of the factor corresponding to the base of zero level [2][3][4][5][8][9]0. The level and coding of the independent variables are presented in **Table 1.**

Table 1 Level of independent variables for Ti-6Al-4V

Levels	Lowest	Low	Center	High	Highest
Coding	-1.4142	-1	0	1	1.4142
Cutting Speed, V	124.53	130	144.22	160	167.03
Feed, f_z	0.025	0.03	0.046	0.07	0.083
Radial Rake Angle, (RRA), γ	6.16	7	9.54	13	14.78

3.3Experimental set-up

A Taylor Hobson Surftronic +3 was used to measure the surface roughness on the machined workpiece of the Ti-6Al-4V rectangular block.

End milling tests were carried out on a CNC MAHO 700S machining centre with a constant a_a (axial depth of cut) 5 mm and a_p (radial depth of cut) 2 mm under wet conditions using 6% of water base coolant. Fresh solid carbide end mill, grade K30 with different radial rake angle was used for each machining trials. A sequentially experiments was conducted for screening the significant factors using 3F1-factorial design augmented with 4 center points and followed with CCD design with 1 replication for each star point. The analysis of mathematical models was carried out using Design Expert 6.0 package for both first and second order models.

The cutting conditions, factors used in the experimental trials and the surface roughness values obtained is presented in Table 2.

Table 2 Cutting condition in coded factors and R_a results

Standard	Type	Factor 1 A, V(m/min)	Factor 2 B, f_z(mm/th)	Factor 3 C, γ (°)	Surface roughness, R_a (μm)
1	Factorial	-1	-1	-1	0.365
2	Factorial	1	-1	-1	0.256
3	Factorial	-1	1	-1	0.498
4	Factorial	1	1	-1	0.464
5	Factorial	-1	-1	1	0.428
6	Factorial	1	-1	1	0.252
7	Factorial	-1	1	1	0.561
8	Factorial	1	1	1	0.512
9	Center	0	0	0	0.464
10	Center	0	0	0	0.444
11	Center	0	0	0	0.448
12	Center	0	0	0	0.424
13	Axial	-1.4142	0	0	0.328
14	Axial	-1.4142	0	0	0.324
15	Axial	1.4142	0	0	0.236
16	Axial	1.4142	0	0	0.240
17	Axial	0	-1.4142	0	0.252
18	Axial	0	-1.4142	0	0.262
19	Axial	0	1.4142	0	0.584
20	Axial	0	1.4142	0	0.656
21	Axial	0	0	-1.4142	0.304
22	Axial	0	0	-1.4142	0.288
23	Axial	0	0	1.4142	0.316
24	Axial	0	0	1.4142	0.348

4. RESULTS AND DISCUSSIONS

4.1 Development first order model using CCD design.

From the experimental results, empirical equations were developed to estimate surface roughness and the significant parameters involved i.e. cutting speed, feed rate and radial rake angle. The first order model obtained from above functional relationship using the RSM method is as follows:

$$\hat{y}_1 = -0.87922 - 0.13082x_1 + 0.23561x_2 + 0.04513x_3 \quad \textbf{(7)}$$

By substituting Eq. 6 in Eq. 7, the transformed equation of surface roughness prediction is as follows:

$$R_a = 871.937V^{-1.26007} f_z^{0.55614} \gamma^{0.14581} \quad \textbf{(8)}$$

The analysis of variance (ANOVA) of linear CCD model is as follows:

Table 3 ANOVA of linear CCD model

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	0.60	3	0.20	14.97	0.0012	significant
A	0.14	1	0.14	10.29	0.0125	
B	0.44	1	0.44	33.40	0.0004	
C	0.016	1	0.016	1.23	0.3005	
Residual	0.11	8	0.013			
Lack of Fit	0.10	5	0.020	14.84	0.0251	significant
Pure Error	4.134E-003	3	1.378E-003			
Cor Total	0.70	11				

From the ANOVA, it is obvious to recognize that the lack of fit (LOF) of the linear CCD model was significant. Therefore, this model cannot be used to predict surface roughness value.

4.2 Development second order model using 3F1 design

The 3F1-model in coded variables, which was obtained using the experimental data in Table 2 from standard 1 to 12, is as follows:

$$\hat{y} = -0.91374 - 0.13082\ x_1 + 0.23561\ x_2 + 0.04513\ x_3 + 0.090288\ x_1 x_2 \quad \textbf{(9)}$$

To prove the adequacy of the model, ANOVA was carried out and results are presented in Table 4.

Table 4 ANOVA of 3F1-factorial model

Response: Surface Roughness Ra 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	0.66	4	0.17	78.99	< 0.0001	significant
A	*0.14*	*1*	*0.14*	*65.29*	*0.0002*	
B	*0.44*	*1*	*0.44*	*211.80*	*< 0.0001*	
C	*0.016*	*1*	*0.016*	*7.77*	*0.0317*	
AB	*0.065*	*1*	*0.065*	*31.10*	*0.0014*	
Curvature	0.029	1	0.029	13.63	0.0102	significant
Residual	0.013	6	2.097E-003			
Lack of Fit	*8.447E-003*	*3*	*2.816E-003*	*2.04*	*0.2861*	*not significant*
Pure Error	*4.134E-003*	*3*	*1.378E-003*			
Cor Total	0.70	11				

This equation is valid for the end milling of titanium alloy, Ti-6Al-4V using solid carbide under wet conditions with the following range of respective cutting speed V, feed per tooth f_z and radial rake angle γ: $130 \leq V \leq 160$ m.min^{-1}; $0.03 \leq f_z \leq 0.07$ mm/tooth; $7 \leq \gamma \leq 13$ (^{o}) . Some of possible solutions for the 3F1 model are presented in Table 5

Table 5 Possible solutions of 3F1-factorial model

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
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
Surface Rough	minimize	0.251999	0.561	1	1	3

Solutions

Number	Cutting speed	Feed rate fz	Rake angle ra	Surface Rough	Desirability	
1	158.19	0.03	7.19	0.250829	1.000	Selected
2	159.96	0.03	7.95	0.246998	1.000	
3	157.74	0.03	7.00	0.251718	1.000	
4	159.79	0.03	7.06	0.247255	1.000	
5	159.59	0.03	7.57	0.24795	1.000	
6	158.59	0.03	7.05	0.248904	1.000	
7	159.86	0.03	9.23	0.251856	1.000	
8	159.43	0.03	7.55	0.247714	1.000	
9	159.46	0.03	8.67	0.251612	1.000	
10	160.00	0.03	7.00	0.251976	1.000	
11	160.00	0.03	9.90	0.253603	0.992	
12	156.90	0.03	7.00	0.254141	0.989	
13	160.00	0.03	10.71	0.256729	0.977	
14	160.00	0.03	12.65	0.264332	0.940	
15	160.00	0.03	12.75	0.264702	0.939	

The response surface of 3F1-model (Fig. 2) reveals that the most significant factor influencing the surface roughness was feed rate and followed by cutting speed and radial rake angle.

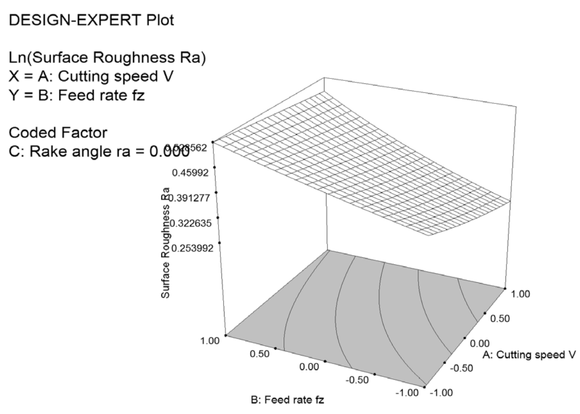

Fig. 2 The response surface of the 3F1-model

4.3 Development second order model using CCD design

Further evaluation on the higher order model was carried out using the CCD, which is achieved with augmentation of 3F1-factorial design and additional replicated star points (Fig. 1). Results in Table 6 indicate that the quadratic CCD model is more significant than linear model and it is also proven that linear model has a significant LOF. Therefore, the quadratic model was chosen in order to build the CCD model.

Table 6 Fit and summary test o the higher order CCD model

Response: Surface Roughness Ra 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	23.97	1	23.97			
Block	0.35	1	0.35			
Linear	1.46	3	0.49	22.39	< 0.0001	
2FI	0.071	3	0.024	1.10	0.3766	
Quadratic	0.30	3	0.099	28.42	< 0.0001	Suggested
Cubic	0.027	4	6.807E-003	3.41	0.0585	Aliased
Residual	0.018	9	1.998E-003			
Total	26.18	24	1.09			

The second order surface roughness model thus developed is given below:

$$\hat{y} = -0.9303 - 0.12103\ x_1 + 0.273219\ x_2 + 0.042714\ x_3 + 0.902088\ x_1x_2 - 0.02446\ x_1x_3 + 0.00926\ x_2x_3 - 0.1139\ x_1^2 + 0.06555\ x_2^2 - 0.05519\ x_3^2 \quad \textbf{(10)}$$

To check the adequacy of the proposed second order CCD model, ANOVA was used and results are shown in the Table 7.

Table 7 ANOVA for the higher order CCD model

Response: Surface Roughness Ra Transform: Natural log Constant: 0
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	0.35	1	0.35			
Model	1.83	9	0.20	58.31	< 0.0001	significant
A	*0.23*	*1*	*0.23*	*67.39*	*< 0.0001*	
B	*1.19*	*1*	*1.19*	*343.45*	*< 0.0001*	
C	*0.029*	*1*	*0.029*	*8.39*	*0.0125*	
A2	*0.16*	*1*	*0.16*	*44.77*	*< 0.0001*	
B2	*0.052*	*1*	*0.052*	*14.83*	*0.0020*	
C2	*0.037*	*1*	*0.037*	*10.51*	*0.0064*	
AB	*0.065*	*1*	*0.065*	*18.75*	*0.0008*	
AC	*4.785E-003*	*1*	*4.785E-003*	*1.38*	*0.2618*	
BC	*6.860E-004*	*1*	*6.860E-004*	*0.20*	*0.6642*	
Residual	0.045	13	3.478E-003			
Lack of Fit	*0.027*	*4*	*6.807E-003*	*3.41*	*0.0585*	*not significant*
Pure Error	*0.018*	*9*	*1.998E-003*			
Cor Total	2.22	23				

ANOVA results indicated that the second order CCD model was valid. The range of the cutting speed V, feed per tooth f_z and radial rake angle γ are: $124.53 \leq V \leq 167.03$ m.min^{-1}; $0.025 \leq f_z \leq 0.083$ mm/tooth; $6.16 \leq \gamma \leq 14.78$ (^{o}) respectively. Results of the surface roughness values at various conditions for the second order CCD model are presented in Table 8.

Table 9 shows the possible solutions of surface roughness values for second order CCD model when using feed rate, $f_z = 0.03$ mm.min^{-1} and radial rake angle, $\gamma = 7.19^o$ at various cutting speeds. Almost similar results were obtained when using the 3F1-model (Table 5).

Table 8 Possible solutions for the second order CCD model

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Cutting speed	is in range	124.53	167.03	1	1	3
Feed rate fz	is in range	0.025	0.08	1	1	3
Rake angle ra	is in range	6.16	14.78	1	1	3
Surface Rougl	minimize	0.236001	0.656	1	1	3

Solutions

Number	Cutting speed	Feed rate fz	Rake angle ra	Surface Rougl	Desirability	
1	166.54	0.05	13.35	0.22755	1.000	Selected
2	158.75	0.03	6.16	0.214314	1.000	
3	156.14	0.03	6.17	0.228876	1.000	
4	166.88	0.04	8.53	0.199685	1.000	
5	164.28	0.03	10.95	0.196401	1.000	
6	165.46	0.04	8.96	0.213899	1.000	
7	160.56	0.03	12.32	0.219077	1.000	
8	158.86	0.03	11.17	0.229874	1.000	
9	165.85	0.04	12.04	0.202071	1.000	
10	159.19	0.03	11.31	0.230573	1.000	
11	156.07	0.03	13.90	0.234346	1.000	
12	165.70	0.05	14.68	0.228068	1.000	
13	165.27	0.04	14.38	0.198673	1.000	
14	124.53	0.03	6.16	0.290006	0.798	
15	124.53	0.03	14.78	0.332988	0.663	

Table 9 Possible solutions for the second order CCD model with f_z =0.03 mm/tooth and $\gamma = 7.19^o$

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Cutting speed	is in range	124.53	167.03	1	1	3
Feed rate fz	is target = 0.0	0.025	0.08	1	1	3
Rake angle ra	is target = 7.1	6.16	14.78	1	1	3
Surface Rougl	minimize	0.236001	0.656	1	1	3

Solutions

Number	Cutting speed	Feed rate fz	Rake angle ra	Surface Rougl	Desirability	
1	158.70	0.03	7.19	0.226525	1.000	Selected
2	164.75	0.03	7.19	0.189501	1.000	
3	162.04	0.03	7.19	0.20624	1.000	
4	164.84	0.03	7.19	0.188992	1.000	
5	160.20	0.03	7.19	0.217484	1.000	
6	166.10	0.03	7.19	0.181176	1.000	
7	164.57	0.03	7.19	0.19062	1.000	
8	158.25	0.03	7.20	0.229312	1.000	
9	124.53	0.03	7.19	0.309524	0.902	
10	124.69	0.03	7.19	0.309916	0.902	
11	124.53	0.03	7.22	0.310004	0.900	

Fig. 3 shows that at the midpoint of the experiments, the response surface forms a curve that is not covered by the 3F1 model. This extended region was obtained when the second order CCD model was used in developing the surface roughness model. Both contours had a similar trend at higher cutting speed. In contrary at lower cutting speed, the trend of the contour tends to increase.

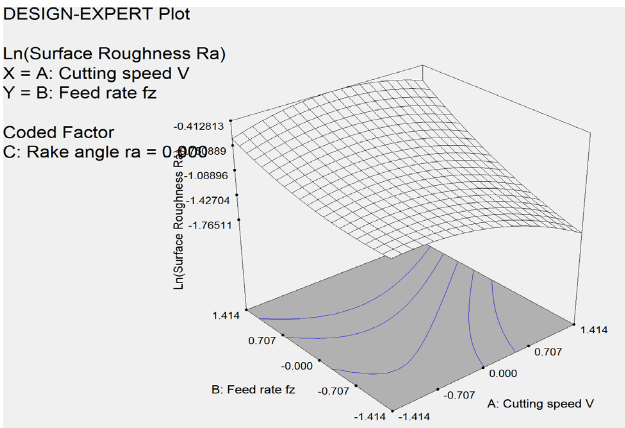

Fig. 3 The response surface of the second order CCD-model

5. CONCLUSIONS

1. Cutting speed, feed rate and radial rake angle are the primary factors influencing the surface roughness when end milling Ti-6Al4V.
1. Two second order models can represent the functional relationship between the investigated cutting parameters. They are 3F1 and second order CCD models with different covering region of experimental data.
2. Based on the second order CCD model, lower surface roughness can be obtained by employing higher cutting speed, low feed rate and higher radial rake angle.
3. Compared to linear CCD model, the results of 3F1-model are better in terms of curvature effect, which is not covered by the linear CCD model.
4. The second order CCD model produced almost the same results to that of 3F1-model when tested at feed rate, f_z = 0.03 mm.min^{-1} and radial rake angle, $\gamma = 7.19^o$.

ACKNOWLEDGEMENTS

The authors wish to thank the Research Management Center, UTM and the Ministry of Science, Technology and Innovation Malaysia for their financial support to the above project through the IRPA funding 03-02-02-0068 PR0074/03-01 – Vote no. 74545.

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