Modeling for Surface Roughness in End-Milling of Titanium Alloy Ti-6Al-4V Using Uncoated WC-Co and PCD Inserts

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Abstract:
This paper presents an approach to optimize the surface finish in end milling titanium-alloy of Ti-6Al-4V using uncoated WC-Co and PCD inserts under dry conditions. Response surface methodology is utilized to develop an efficient mathematical model for surface roughness in terms of cutting speed, feed and axial depth of cut. For this purpose, a number of machining experiments based on factorial design of experiments method are carried out in order to determine surface roughness values. The 3FI surface roughness models have been developed at 95% confidence interval for both the inserts. The adequacy of the models has been verified by analyzing the variance.

Keywords: Surface roughness, Model, PCD, Uncoated WC-Co, RSM

1. Introduction

Titanium alloys are widely known as difficult to cut materials, especially at higher cutting speeds, due to their several inherent properties. Among all titanium alloys, Ti-6Al-4V is most widely used, so it has been chosen as the workpiece material in this study. Siekmann [1] suggested that machining of titanium and its alloys would always be a problem, no matter what techniques are employed to transform this metal into chips. When machining Ti-6Al-4V, conventional tools wear rapidly because the poor thermal conductivity of titanium alloys resulting in higher cutting temperature closer to the cutting edge. There also exists strong adhesion between the tool and workpiece material [2]. Since the performance of conventional tools is poor in machining Ti-6Al-4V, a number of newly evolved tool materials, such as cubic boron nitride (CBN) and polycrystalline diamond (PCD), are being considered to achieve high-speed milling [3].

In order to establish an adequate functional relationship between the responses (such as surface roughness, cutting force, tool life/wear) and the cutting parameters (cutting speed, feed, and depth of cut), a large number of tests are needed for each and every combination of cutting tool and work piece materials. This increases the total number of tests and as a result the experimentation cost also increases. Response Surface Methodology (RSM), a group of mathematical and statistical techniques, is useful for modeling the relationship between the input parameters (cutting conditions) and the output-variables. RSM saves cost and time by reducing the number of experiments required to be conducted.

A machinability model may be defined as a functional relationship between the input of independent cutting variables (speed, feed, depth of cut) and the output known as responses (tool life, surface roughness, cutting force, etc) of a machining process [4].

Response surface methodology (RSM) is a combination of experimental and regression analysis and statistical inference. RSM is a dynamic and foremost important tool of design of experiment (DOE), wherein the relationship between response(s) of a process with its input decision variables is mapped to achieve the objective of maximization or minimization of the response properties [5-6]. Many machining researchers have used response surface methodology to design their experiments and assess results. Kaye et al [7] used response surface methodology in predicting tool flank wear using spindle speed change. A unique model has been developed which predicts tool flank wear, based on the spindle speed change, provided the initial flank wear at the beginning of the normal cutting stage is known. An empirical equation has also been derived for calculating the initial flank wear, given the speed, feed rate, depth of cut and workpiece hardness. Alauddin et al [8] applied response surface methodology to optimize the surface finish in end milling of Inconel 718 under dry condition. They developed contours to select a combination of cutting speed, and feed without increasing the surface roughness.

Fuh and Wang [9] developed a model for predicting milling force model in end milling operation. They found that the proposed model is suitable for practical engineering application, since the milling force analyzed in the model has already encompassed the structural characteristics of the milling machine and the real conditions of the tool and workpiece. They also suggested that the proposed force model had a good correlation with experimental values. Choudhury and el-Baradie [10] found that response surface methodology combined with the factorial design of experiments were useful techniques for tool life testing. Relatively, a small number of designed experiments are required to generate much useful information that can be used for developing the predicting equation for tool life. Mansour and Abdalla [11] developed a surface roughness model for end milling of a semi-free cutting carbon casehardened steel. They investigated a first-order equation covering the speed range 30 – 35 m/min and a second order generation equation covering the speed range 24 – 38 m/min. They suggest that an increase in either the feed or the axial depth of cut increases the surface roughness, whilst an increase in the cutting speed decreases the surface roughness. Oktem et al [12] used response surface methodology with a developed genetic algorithm (GA) in the optimization of cutting conditions for surface roughness. S. Sharif et al [13] used factorial design coupled with response surface methodology in developing the surface roughness model in relation to the primary machining variables such as cutting speed, feed, and radial rake angle.

In this paper, the RSM technique is used in developing a mathematical model to optimize the surface roughness values when end milling titanium alloy using both uncoated WC-Co and PCD inserts under dry conditions. Factorial design coupled with response surface methodology is utilized to develop the model for predicting surface roughness values.

Mathematical Model

Surface roughness model for end milling in terms of the parameters can be expressed in general terms as:

$$R_a = C V^k f_z^l a^m \tag{1}$$

Where R_a is the predicted surface roughness (μm), V is the cutting speed (m/min), f_z is the feed per tooth (mm/tooth), and a is the axial depth of cut (mm). C, k, l, and m are model parameters to be estimated using the experimental results. To determine the constants and exponents, this mathematical model can be linearized by employing a logarithmic transformation, and Eq. (1) can be re-expressed as:

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

The linear model of Eq. 2 is :

$$y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \tag{3}$$

where y is the true response of surface roughness on a logarithmic scale; $x_0 = 1$ (dummy variable), x_1, x_2, x_3 are logarithmic transformations of speed, depth of cut, and feed, respectively, while β_0, β_1, β_2, and β_3 are the parameters to be estimated. Eq. (3) can be expressed as:

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

where $\hat{y}$ is the estimated response and y the measured surface roughness on a logarithmic scale, ε the experimental error and the b values are estimates of the β parameters.

The second-order model can be extended from the first-order model equation as:

$$\hat{y}_2 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \tag{5}$$

where $\hat{y}_2$ is the estimated response based on the second order model. Analysis of variance is used to verify and validate the model.

2. Experiment details

2.1 Machining

End milling tests were conducted on Vertical Machining Centre (VMC ZPS, Model: MLR 542) with full immersion cutting under dry conditions. Machining was performed with a 20 mm diameter end-mill tool holder fitted with one insert. Uncoated WC-Co and PCD inserts were used in the experiments. Mitutoyo SURFTEST SV-500 was used to measure the surface roughness.

2.2 Coding of the independent variables

The independent variables were coded taking into consideration the limitation and capacity of the cutting tools. Levels of independent and coding identification are presented in Table 1 and Table 2, for experiment using uncoated WC-Co and PCD inserts, respectively.

Table 1: Coding Identification for end milling using WC-Co inserts

Levels	Lowest	Low	Centre	High	Highest
Coding	$-\sqrt{2}$	-1	0	+1	$+\sqrt{2}$
x_1, cutting speed, V (m/min)	30.59	39	70.1	126	160.6
x_2, axial depth of cut, a (mm)	0.5	0.61	1	1.65	2.03
x_3, feed, f_z (mm/tooth)	0.05	0.06	0.088	0.128	0.15

The transforming equations for each of the independent variables are:

$$x_1 = \frac{\ln V - \ln 70.1}{\ln 126 - \ln 70.1};\ x_2 = \frac{\ln a - \ln 1}{\ln 1.65 - \ln 1};\ x_3 = \frac{\ln f_z - \ln 0.088}{\ln 0.128 - \ln 0.088} \tag{6}$$

Table 2: Coding Identification for end milling using PCD inserts

Levels	Lowest	Low	Centre	High	Highest
Coding	$-\sqrt{2}$	-1	0	+1	$+\sqrt{2}$
x_1, cutting speed, V (m/min)	80.53	92	126.9	175	200
x_2, axial depth of cut, a (mm)	0.5	0.61	1	1.65	2.03
x_3, feed, f_z (mm/tooth)	0.05	0.06	0.088	0.128	0.15

The transforming equations for each of the independent variables are:

$$x_1 = \frac{\ln V - \ln 126.89}{\ln 175 - \ln 126.89};\ x_2 = \frac{\ln a - \ln 1}{\ln 1.65 - \ln 1};\ x_3 = \frac{\ln f_z - \ln 0.088}{\ln 0.128 - \ln 0.088} \tag{7}$$

2.3 Experimental Design

The design of the experiments has an effect on the number of experiment required. Therefore, it is important to have a well-designed experiment to minimize the number of experiments which often are carried out randomly. In the experiment, factorial design of experiment augmented with 4 centre points was used to develop the second order model. The analysis of mathematical models was carried out using Design-expert 6.0 package. Cutting conditions in coded factors and the surface roughness values obtained using uncoated WC-Co and PCD inserts are presented in Table 3.

Table 3: Surface Roughness results and cutting conditions in coded factors

Standard Order	Type	Coding of Level			R_a, Surface Roughness (μm)	
		x_1	x_2	x_3	WC-Co	PCD
1	Factorial	1	-1	-1	0.33	0.50
2	Factorial	-1	1	-1	0.38	0.35
3	Factorial	-1	-1	1	0.33	0.86
4	Factorial	1	1	1	0.40	0.80
5	Factorial	1	1	-1	0.33	0.85
6	Factorial	1	-1	1	0.41	0.81
7	Factorial	-1	-1	-1	0.17	0.32
8	Factorial	-1	1	1	0.37	0.95
9	Centre	0	0	0	0.22	0.43
10	Centre	0	0	0	0.24	0.45
11	Centre	0	0	0	0.23	0.45
12	Centre	0	0	0	0.23	0.52

4. Results and discussions

4.1 Uncoated WC-Co inserts

The 3FI-model in terms of coded variables obtained from the experimental data in Table 3, is as follows:

$$\hat{y} = -1.11 + 0.1x_1 + 0.11x_2 + 0.13x_3 - 0.12x_1x_2 - 0.089x_2x_3 + 0.083x_1x_2x_3 \quad (8)$$

The analysis of variance of 3FI model is presented in Table 4. The model F-value of 35.85 implies that the model is significant. There is only a 0.20% chance that a *model F-Value* this large could occur due to noise. The *Curvature F-Value* of 136.29 implies that there is a significant curvature (as measured by difference between the average of the centre points and the average of the factorial points) in the design space. There is only a 0.03% chance that a *Curvature F-Value* this large could occur due to noise. The *lack of fit F-Value* of 5.11 implies that there is a 10.88% chance that a lack of fit *F-Value* this large could occur due to noise. Non-significant lack of fit is good, therefore, we can use the model to navigate the design space.

The 3FI second order model (Eq. 8), indicates that feed gives significant effect on surface roughness, followed by axial depth of cut and cutting speed. Interaction between cutting speed and axial depth of cut also has a significant effect on surface roughness values. This equation is valid for end milling of titanium alloy Ti-6Al-4V under dry condition using uncoated WC-Co inserts with the following range of cutting speed V, feed f_z, and axial depth of cut a : $39 \leq V \leq 126$ m/min, $0.61 \leq a \leq 1.65$ mm, and $0.06 \leq f_z \leq 0.128$ mm/tooth, respectively. Figure 1 presents the contours of surface roughness resulting from the experiments and predicted values generated by the model. The contours indicated that the predicted surface roughness values are very close to the actual (experimental) values. We can affirm that the model can be used to predict the surface roughness values. Figure 2 presents the response surface of the 3FI model for end milling using WC-Co inserts at $x_3 = 0.081$. The graph implies that lower surface roughness values can be achieved by employing low cutting speed and low axial depth of cut. Figure 3, Figure 4, and Figure 5 present the contours of surface roughness. The graphs imply that an increase in cutting speed, axial depth of cut, and feed result in an increase in surface roughness values.

Table 4: ANOVA of 3FI-model for end milling using uncoated WC-Co inserts

Source	SS	DF	MS	F Value	Prob > F	
Model	0.5506	6	0.0918	35.853	0.0020	Significant
x_1	0.0835	1	0.0835	32.617	0.0046	
x_2	0.0999	1	0.0999	39.039	0.0033	
x_3	0.1368	1	0.1368	53.439	0.0019	
$x_1 x_2$	0.1113	1	0.1113	43.471	0.0027	
$x_2 x_3$	0.0638	1	0.0638	24.942	0.0075	
$x_1 x_2 x_3$	0.0553	1	0.0553	21.614	0.0097	
Curvature	0.3489	1	0.3489	136.29	0.0003	Significant
Residual	0.0102	4	0.0026			
Lack of Fit	0.0065	1	0.0065	5.112	0.1088	Not-significant
Pure Error	0.0038	3	0.0013			
Cor Total	0.9097	11				

x_1 : cutting speed, x_2 : axial depth of cut, x_3 : feed

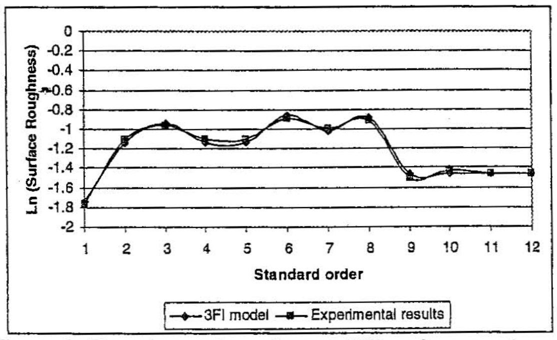

Figure 1: Experimental results and 3FI surface roughness values using uncoated WC-Co inserts

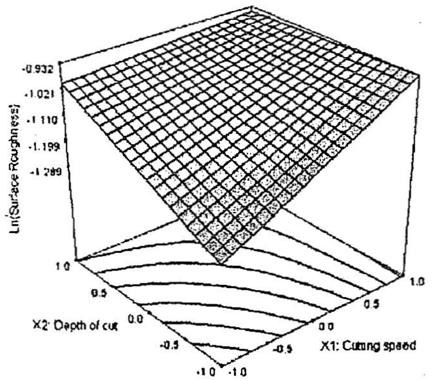

Figure 2: The 3D surface of the 3FI-model at $x_3 = 0.081$ for experiments using uncoated WC-Co inserts

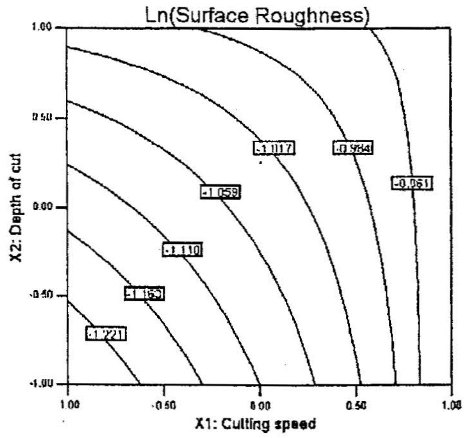

Figure 3: The surface contours of the 3FI-model at $x_3 = 0.5$ for experiments using uncoated WC-Co inserts

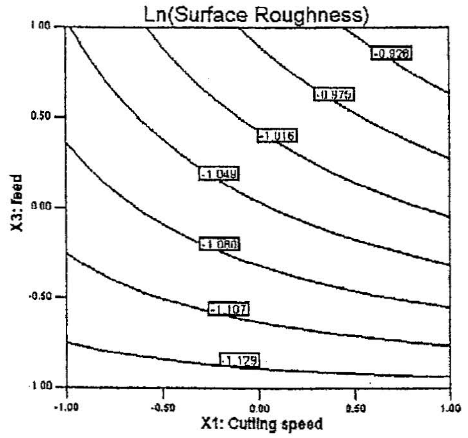

Figure 4: The surface contours of the 3FI-model at $x_2 = 0.5$ for experiments using uncoated WC-Co inserts

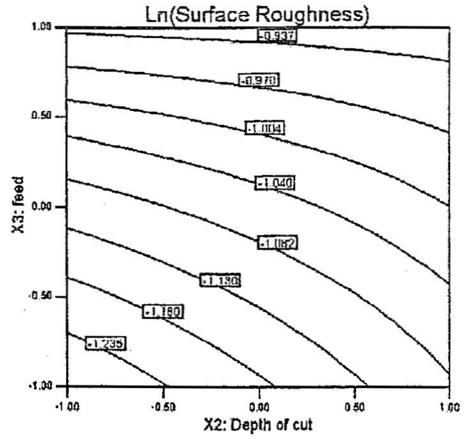

Figure 5: The surface contours of the 3FI-model at $x_1 = 0.5$ for experiments using uncoated WC-Co inserts

4.2 PCD inserts

The 3FI-model in coded variables obtained from the experimental data of Table 3, is expressed as follows:

$$\hat{y} = -0.46 + 0.14x_1 + 0.088x_2 + 0.3x_3 + 0.04x_1x_2 - 0.2x_1x_3 - 0.067x_2x_3 \qquad (9)$$

The analysis of variance of 3FI model is presented in Table 5. The model F-value of 14.7 implies that the model is significant. There is only a 1.07% chance that a Model F-Value this large could occur due to noise. The curvature F-Value of 17.86 implies that there is a significant curvature (as measured by difference between the average of the centre points and the average of the factorial points) in the design space. There is only a 1.34% chance that a *Curvature F-Value* this large could occur due to noise. The *lack of fit F-Value* of 5.59 implies that there is a 9.9% chance that a lack of fit *F-Value* this large could occur due to noise. Non-significant lack of fit is good, therefore, we can use the model to navigate the design space.

The 3FI second order model (Eq. 9) indicates that feed gives the highest significant effect on surface roughness, followed by cutting speed and axial depth of cut. Interaction between cutting speed and feed will also have a significant effect on the surface roughness values. This equation is valid for end milling of titanium alloy Ti-6Al-4V under dry condition using PCD inserts. with the following range of cutting speed V, feed f_z, and axial depth of cut a: $92 \leq V \leq 175$ mm/min, $0.61 \leq a \leq 1.65$ mm, and $0.06 \leq f_z \leq 0.128$ mm/tooth, respectively. Figure 3 presents the contours of surface roughness resulting from the experiments and predicted values generated by the model. The contours indicated that the predicted surface roughness values are very close the actual (experimental) values. Figure 4 presents the 3D surface of the 3FI model for experiments using PCD inserts. The graph shows that lower surface roughness values can be achieved by using low cutting speed and low axial depth of cut. Figure 8, Figure 9, and Figure 10 present the contours of surface roughness. The graphs imply that an increase in cutting speed, axial depth of cut, and feed result in an increase in surface roughness values.

Tabel 5: ANOVA of the- 3FI-model for end milling using PCD inserts

Source	SS	DF	MS	F Value	Prob > F	
Model	1.2950	6	0.2158	14.699	0.0107	significant
x_1	0.1518	1	0.1518	10.335	0.0324	
x_2	0.0625	1	0.0625	4.259	0.1080	
x_3	0.7254	1	0.7254	49.399	0.0022	
x_1x_2	0.0135	1	0.0135	0.922	0.3914	
x_1x_3	0.3063	1	0.3063	20.858	0.0103	
x_2x_3	0.0355	1	0.0355	2.420	0.1948	
Curvature	0.2623	1	0.2623	17.861	0.0134	significant
Residual	0.0587	4	0.0147			
Lack of Fit	0.0382	1	0.0382	5.589	0.0990	not significant
Pure Error	0.0205	3	0.0068			
Cor Total	1.6160	11				

x_1 : cutting speed, x_2 : axial depth of cut, x_3 : feed

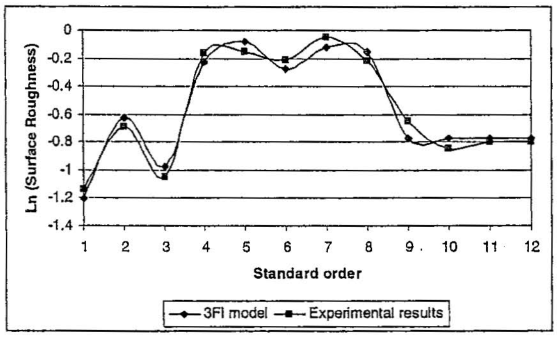

Figure 6: Experimental results and 3FI surface roughness values using PCD inserts

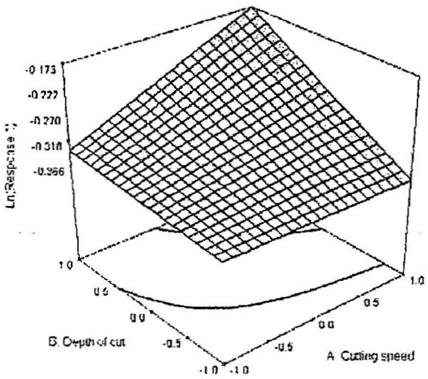

Figure 7: The 3D surface of the 3FI-model at $x_3 = 0.5$ for experiments using PCD inserts

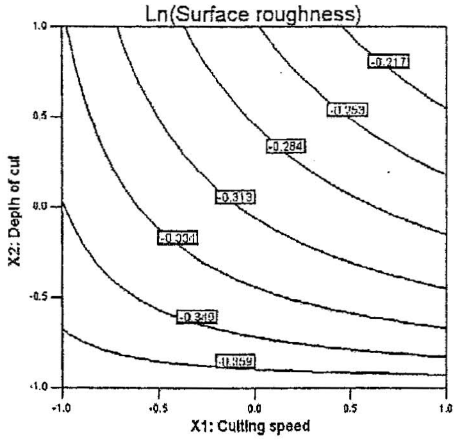

Figure 8: The surface contours of the 3FI-model at $x_3 = 0.5$ for experiments using PCD inserts

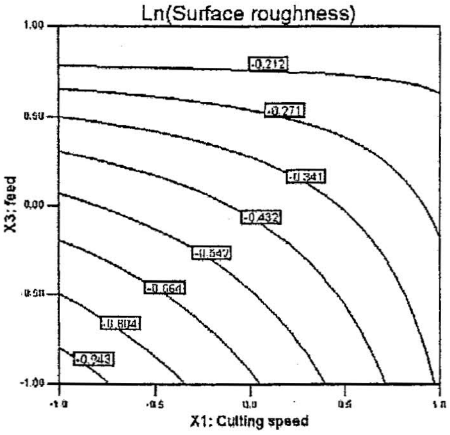

Figure 9: The surface contours of the 3FI-model at $x_2 = 0.5$ for experiments using PCD inserts

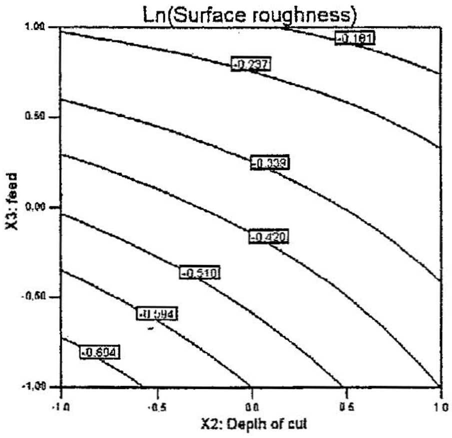

Figure 10: The surface contours of the 3FI-model at $x_1 = 0.5$ for experiments using PCD inserts

5. Conclusions

1. Factorial design has been proved to be a successful technique to predict the surface roughness produced in end-milling of titanium alloy Ti-6Al-4V using uncoated WC-Co and PCD inserts under dry conditions.
2. The 3FI second order model developed by RSM using Design Expert package was able to provide accurately predicted values of surface roughness close to actual values found in the experiments. The equation was checked for their adequacy with a confidence level of 95%.
3. The two models (for WC-Co and PCD inserts) indicate that the feed has the most significant influence on surface roughness, followed by cutting speed and axial depth of cut.
4. Interaction effect between cutting speed and feed also has a high effect on surface roughness values.

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