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Optimization of Surface Roughness in End Milling of Titanium Alloy Ti-6Al-4V under the Influence of Magnetic Field from Permanents Magnets

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Abstract. This paper presents the effect of cutting parameters on surface roughness in end milling of Titanium alloy Ti-6Al-4V under the influence of magnetic field from permanent magnets. Response Surface Methodology (RSM) with a small central composite design was used in developing the relationship between cutting speed, feed, and depth of cut, with surface roughness. In this experiment, three factors and five levels of central composite with 0.16817 alpha value was used as an approach to predict the surface roughness, in end milling of titanium alloy, with reasonable accuracy. The Design-Expert 6.0 software was applied to develop the surface roughness equation for the predictive model. The adequacy of the surface roughness model was validated to 95% by using ANOVA analysis. Finally, desirability function approach was used to determine the optimum possible surface roughness given the capabilities of the end machine.

Introduction

Response Surface Methodology (RSM) comprises a body of methods for exploring the optimum operating condition through experimental method. The aim of such experimentation is to find out how a number of experimental variables affect the response [1]. Many machining researchers have used RSM to design their experiments and assess the results. Turnad et al. [2] used response surface methodology in developing first and second order model for surface roughness in end milling of Ttitanium alloy. An empirical equation has also been derived for calculating the surface roughness. Alauddin et al. [3] applied RSM 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. Funda [4] used RSM in predicting surface roughness of AISI 4140 steel. His work showed that cutting speed and feed rate have the most significant effect on surface roughness. Mansour et al. [5] developed a surface roughness model for end milling of a semi free cutting carbon case hardened 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. Patwari et al. [6] applied RSM for optimization of surface roughness in end milling of medium carbon steel by using genetic algorithm approach. They obtained an optimum average surface roughness of 0.7405 μm for machining of medium carbon steel AISI 1045 at 207.74 m/min of cutting speed, 1.149 mm of depth of cut, and 0.0556 mm/tooth of feed. Senussi [7] used RSM to present the cause and effect of the relationship between true mean response (chip micro hardness of 304- Austenitic stainless steel) and input control variables (cutting speed, feed rate, depth of cut, and distance from the centre of workpiece). The result showed that micro hardness of chips of 304 – Austenitic stainless steel increased at low cutting speed and high feed rate and large diameter of work piece. In this paper, a CCD of experiments was used to develop a mathematical model for prediction of surface roughness in end milling of Ti-6Al-4V. Machining was done using uncoated WC-Co insert under the influence of magnetic field from two permanent magnets located at mutually perpendicular directions with respect to the tool axis. The predicted surface roughness values are presented in term of mean values at 95% confidence interval. The optimum surface roughness was then predited using the desirability function approach.

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Experimental Details

Experimental tests were conducted on Vertical Machining Center (VMC ZPS, Model: 1060) with a maximum spindle speed of 8000rpm under the influence of magnetic field from permanent magnets located at mutually perpendicular directions with respect to the tool axis. Two ferrite magnets bar with dimension 1inch x 6 inches x 3 inches were mounted near the cutting tool by specially designed fixture. The strength of these magnets were 2500-2700 Gauss. Machining was performed with a 20 mm diameter end mill tool holder fitted with one uncoated WC-Co insert. Mitutoyo SURFTEST SV-500 was used to measure the surface roughness.

The independent variables were coded taking into consideration the limits for end milling of titanium alloy. The relationships between the coded factors and the actual factors are shown in Equation 1-3, and table 1, below, displays the physical ranges of the three parameters.

$$x_1 = \frac{speed-(speed\ low+speed\ high)/2}{(speed\ high-speed\ low)/2} \quad (1)$$

$$x_2 = \frac{feed-(feed\ low+feed\ high)/2}{(feed\ high-feed\ low)/2} \quad (2)$$

$$x_3 = \frac{doc-(doc\ low+doc\ high)/2}{(doc\ high-doc\ low)/2} \quad (3)$$

Table 1: Level of the Independent Variables

Levels	Lowest	Low	Centre	High	Highest
Coding	-1.681	-1	0	+1	+1.681
x_1, Cutting speed,V(m/min)	19.55	40	70	100	120.45
x_2, Feed, f_z (mm/tooth)	0.02	0.05	0.1	0.15	0.18
x_3, Depth of cut, d(mm)	0.24	0.5	0.88	1.25	1.51

Results and Discussion

In this experiment, a small central composite design with (Alpha = 1.862) was employed to develop the surface roughness model. Surface roughness results in end milling of Ti-6Al-4V with uncoated WC-Co insert are shown in Table 2, below. Fit and Summary test from Table 3, below, suggested that the second order model was the most significant model for predicting the surface roughness in end milling of titanium alloy. The analysis of variance (ANOVA) was used to check the adequacy of the developed model by utilizing the Design Expert 6.0.8 software. From the ANOVA analysis (Table 4, below) the "Model F-Value" of 38.91 implied that the model was significant. There was only a 0.04% chance that a "Model F-Value" this large could occur due to noise. The Lack of Fit value of 1.03 implied that the LOF was significant. There was only a 36.62 chance that a "LACK Of Fit F-Value" this large could occur as a result of noise. Therefore, the quadratic model was chosen in order to develop the CCD model.

Table 2: Surface roughness result and cutting condition in coded factors

No	Type	Coding of levels			Surface roughness (um)
		x_1	x_2	x_3	
1	Fact	1	1	-1	0.58
2	Fact	1	-1	1	0.4
3	Fact	-1	1	1	0.55
4	Fact	-1	-1	-1	0.27
5	Axial	-1.682	0	0	0.54
6	Axial	1.682	0	0	0.4
7	Axial	0	-1.682	0	0.22
8	Axial	0	1.682	0	0.81
9	Axial	0	0	-1.682	0.33
10	Axial	0	0	1.682	0.46
11	Center	0	0	0	0.18
12	Center	0	0	0	0.24
13	Center	0	0	0	0.26
14	Center	0	0	0	0.26
15	Center	0	0	0	0.26

Table 3: Fit and summary test for surface roughness model

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Mean	2.21	1	2.21			
Linear	0.23	3	0.077	4.21	0.0327	
2FI	0.025	3	0.008199	0.37	0.7741	
Quadratic	**0.17**	**3**	**0.056**	**46.67**	**0.0004**	**Suggested**
Cubic	0.001244	1	0.001244	1.04	0.3662	Aliased
Residual	0.0048	4	0.0012			
Total	2.64	15	0.18			

Table 4: Analysis of variance for surface roughness model

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	0.42	9	0.047	38.91	0.0004	significant
A	0.0098	1	0.0098	8.11	0.0359	
B	0.17	1	0.174	143.99	< 0.0001	
C	0.00845	1	0.0084	6.99	0.0458	
A^2	0.078	1	0.078	64.70	0.0005	
B^2	0.11	1	0.113	93.88	0.0002	
C^2	0.034	1	0.034	28.10	0.0032	
AB	0.000437	1	0.00043	0.36	0.5741	
AC	0.00855	1	0.0085	7.07	0.0449	
BC	0.016	1	0.016	12.91	0.0156	
Residual	0.006044	5	0.00120			
Lack of Fit	0.001244	1	0.00124	1.03	0.3662	not significant
Pure Error	0.0048	4	0.0012			
Cor Total	0.43	14				

The second order surface roughness model is thus:

$$R_a = +0.24 - 0.042x_1 + 0.18x_2 + 0.039x_3 + 0.078\, x_1^2 + 0.094x_2^2 + 0.051\, x_3^2 + 0.060x_1x_3 - 0.082\, x_2\, x_3 \qquad (4)$$

Where x_1 is cutting speed (V), x_2 is feed (f) , x_3 is depth of cut (d). The quadratic model showed that feed had the most significant effect on surface roughness, followed by speed and axial depth of cut. The interaction between feed and depth of cut also had a significant effect on surface roughness value as shown in Fig. 1 below:

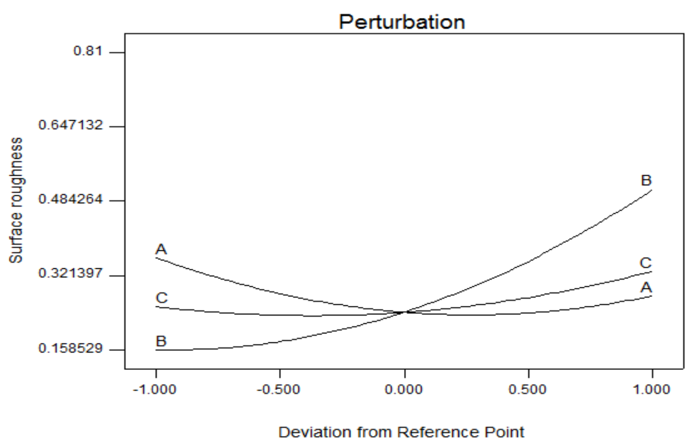
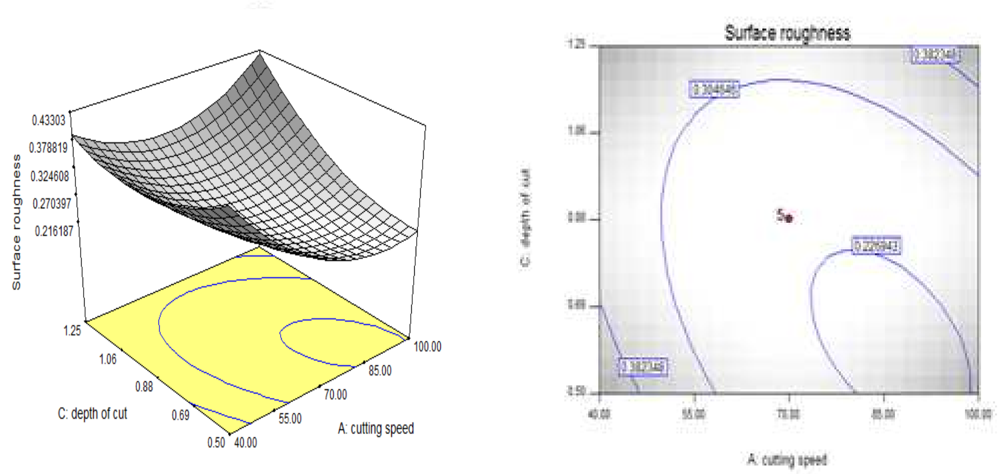


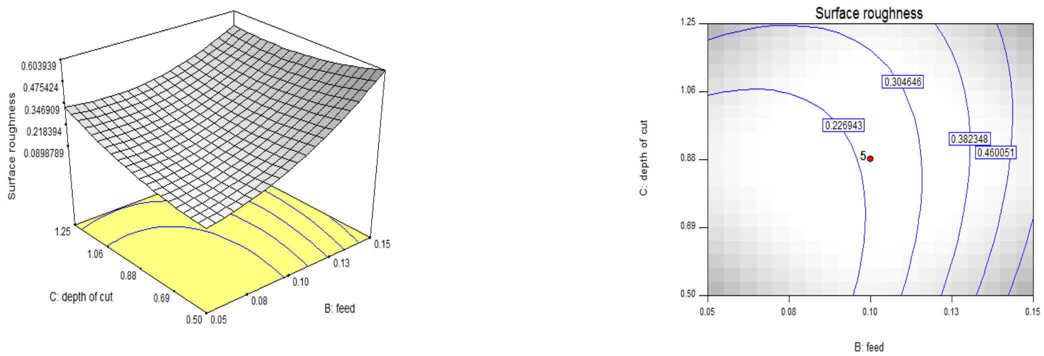
Fig. 1: Pertubation plot for surface roughness

Fig. 1 shows the pertubation plot between three cutting parameters. In this case it was clear that with the increase of feed (B), the surface rouhgness increased and the effect of feed on surface roughness was very significant. The opposite phenomenon was observed for cutting speed (A). The increase of speed resulted in the decrease of surface roughness but the effect of speed on surface roughness was not remarkable like feed. Like wise, depth of cut (C) has less significant effect on surface roughness. The interaction plots in Fig. 3 and 4 illustrate the the relationship in more details.



(a) (b)

Fig. 3: Estimated response surface of Ra vs. depth of cut and cutting speed when feed = 0.10mm/tooth (a) 3D graph and (b) contour graph



(a) (b)

Fig. 4: Estimated response surface of Ra vs. depth of cut and feed when cutting speed = 70m/min (a) 3D graph and (b) contour graph

Therefore, combination of highe cutting speed, lower values of feed and depth of cut was needed to produce low surface finish in cutting the particular Titanium alloy.

The objective of optimization, using desirability function, was to find the best parameters that minimize the response. Table 5, above, presents two possible solutions for optimum cutting parameters in end milling of Ti-6Al-4V using uncoated WC-Co insert. The results showed that the cutting speed of 86 m/min was a probable optimum cutting speed for Titanium alloy. The optimum depth of cut and feed were found to be 0.52 mm and 0.08 mm/tooth. Moreover, surface roughness value of 0.12 µm was the minimum surface roughness that could be achieved with the optimized cutting parameters with 100% desirability.

Table 5: Possible optimum solution for end milling

Number	Cutting speed	Feed	Depth of cut	Surface roughness	Desirability	
1	**86**	**0.08**	**0.52**	**0.12**	**1**	**Selected**
2	62	0.06	0.84	0.17	1	

Conclusions

The following conclusions were drawn based on the results:

1) A quadratic model was developed by RSM for the prediction of surface roughness in end milling of Ti-6Al-4V under the application of magnetic field from permanent magnets.
2) From the developed model it was found that feed had the most significant effect on surface roughness, followed by speed and depth of cut.
3) The optimum cutting speed, feed, and depth of cut were predicted to be 86 m/min, 0.08 mm/tooth, and 0.52 mm, respectively. The value of average surface roughness predicted under this condition is 0.12 μm, which is very good for end milling.

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