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Surface Roughness Prediction Model of 6061-T6 Aluminium Alloy Machining Using Statistical Method

K. Kadirgama
Faculty of Mechanical Engineering, Universiti Malaysia Pahang
Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia
E-mail: kumaran@ump.edu.my
Tel: +6095492242; Fax: +6095492244

M. M. Noor
Faculty of Mechanical Engineering, Universiti Malaysia Pahang
Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia
E-mail: muhamad@ump.edu.my
Tel: +6095492223; Fax: +6095492244

M. M. Rahman
Faculty of Mechanical Engineering, Universiti Malaysia Pahang
Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia
E-mail: mustafizur@ump.edu.my
Tel: +6095492207; Fax: +6095492244

M. R. M. Rejab
Faculty of Mechanical Engineering, Universiti Malaysia Pahang
Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia
E-mail: ruzaimi@ump.edu.my
Tel: +6095492238; Fax: +6095492244

C. H. C. Haron
2Faculty of Engineering, Universiti Kebangsaan Malaysia
43600 UKM, Bangi, Selangor, Malaysia
E-mail: chase@vlsi.eng.ukm.my
Tel: +60389216012; Fax: +60389216040

K. A. Abou-El-Hossein
Mechanical Engineering Department, University of Pretoria, South Africa
E-mail: Khaled.abou-el-hossein@up.ac.za
Tel: +27 12 420 3695; Fax: +27 12 362 5087

Abstract

This paper explores on the optimization of the surface roughness of milling mould 6061-T6 aluminium alloys with carbide coated inserts. Optimization of the milling is very important to reduce the cost and time for machining mould. The purposes of this study are to develop the predicting model of surface roughness, to investigate the most dominant variables among the cutting speed, feed rate, axial depth and radial depth and to optimize the parameters. Response surface method based optimization approach was used in this study. It can be seen from the first order model that the feed rate is the most significantly influencing factor for the surface roughness. Second-order model reveals that there is no interaction between the variables and response.

Keywords: Response surface method, Surface roughness, Machining, Aluminium alloys

1. Introduction

Roughness plays an important role to determine how a real object interacts with its environment. Rough surfaces usually wear more quickly and have higher friction coefficients than smooth surfaces. Roughness is often a good predictor of the performance of a mechanical component, since irregularities in the surface may form nucleation sites for cracks or corrosion. Although roughness is usually undesirable, it is difficult and expensive to control in manufacturing. Decreasing the roughness of a surface will usually increase exponentially its manufacturing costs. This often results in a trade-off between the manufacturing cost of a component and its performance in application.

Recent investigation performed by Alauddin *et al.* [1] has revealed that when the cutting speed is increased, productivity can be maximised and, meanwhile, surface quality can be improved. According to Hasegawa *et al*. [2], surface finish can be characterised by various parameters such as average roughness (R_a), smoothening depth (R_p), root mean square (R_q) and maximum peak-to-valley height (R_t). The present study uses average roughness for the characterisation of surface finish, since it is widely used in industry. By using factors such as cutting speed, feed rate and depth of cut, Hashmi et al. [3, 4] developed the surface roughness models and determined the cutting conditions for 190 BHN steel and Inconel 718. EI-Baradie [5] and Bandyopadhyay [6] have shown that by increasing the cutting speed, the productivity can be maximised and, at the same time, the surface quality can be improved. According to Gorlenko [7] and Thomas [8], surface finish can be characterised by various parameters.

Numerous roughness height parameters such as average roughness, smoothening depth, root mean square and maximum peak-to-valley height can be closely correlated. The present study uses average roughness for the characterisation of surface roughness, due to the fact that it is widely adopted in the industry for specifying the surface roughness. Mital and Mehta [9] have conducted a survey of the previously developed surface roughness prediction models and factors influencing the surface roughness. They have found that most of the surface roughness prediction models have been developed for steels.

2. Response Surface Method

Response surface method (RSM) is a collection of statistical and mathematical methods that are useful for the modelling and optimization of the engineering problems. In this technique, the main objective is to optimize the responses that are influencing by various parameters. RSM also quantifies the relationship between the controllable parameters and the obtained response. In modelling of the manufacturing processes using RSM, the sufficient data is collected through designed experimentation. In general, a second order regression model is developed because of first order models often give lack off fit [10]. The study uses the Box-Behnken design in the optimization of experiments using RSM to understand the effect of important parameters. Box-Behnken Design is normally used when performing non-sequential experiments. That is, performing the experiment only once. These designs allow efficient estimation of the first and second –order coefficients. Because Box-Behnken design has fewer design points, they are less expensive to run than central composite designs with the same number of factors. Box-Behnken Design do not have axial points, thus we can be sure that all design points fall within the safe operating. Box-Behnken Design also ensures that all factors are never set at their high levels simultaneously [11-13]. The proposed linear model correlating the responses and independent variables can be represented by the following expression [11]:

$$y = m \times \text{Cutting speed} + n \times \text{Feed rate} + p \times \text{Axial depth} + q \times \text{Radial depth} + C \quad (1)$$

where y is the response, C, m, n, p and q are the constants.

Equation (1) can be written as Equation (2):

$$y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \quad (2)$$

where y is the response, x_0 = 1(dummy variable), x_1= cutting speed, x_2 = feed rate, and x_3 = axial depth. $\beta_0 = C$ and β_1, β_2, and β_3, are the model parameters.

The second-order model can be expressed as Equation (3)

$$y'' = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{11} x_1 x_2 + \beta_{12} x_1 x_3 + \beta_{14} x_2 x_3 \quad (3)$$

3. Experimental Set-up

The experiments were carried out on 6-axis HAAS CNC milling model HAAS Model VF 6D/40 with 360 ~ 480 volts and 50/60 Hz as shown in Figure 1. Total 27 experiments were carried out. Figure 2 shows the 90^0 tool holder that used in the experiments. Ecocool 6210-IT coolant was used in these experiments. Water was added in to the coolant until the mixture of coolant and water reaches the PH ranges from 9.0 to 9.5. Each experiment was stopped after 90 mm cutting length. For the surface roughness measurement surface roughness tester was used. Each experiment was repeated three times using a new cutting edge every time to obtain accurate readings of the surface roughness. The chemical composition of the aluminium alloys workpiece is listed in Table 1. After the investigation, the suitable levels of the factors are used in the statistical software to deduce the design parameters for aluminium alloys (AA6061-T6) as shown in Table 2. The lower and higher speed values are selected of 100 m/s and 180 m/s respectively. The lower and highest values of feed are considered of 0.1 mm/rev and 0.2 mm/rev respectively. For the axial depth, the higher value is 0.2 mm and the lower value is 0.1 mm and for the radial depth the higher value is 5 mm and lower value is 2 mm.

Figure 1: HAAS CNC milling with 6-axis

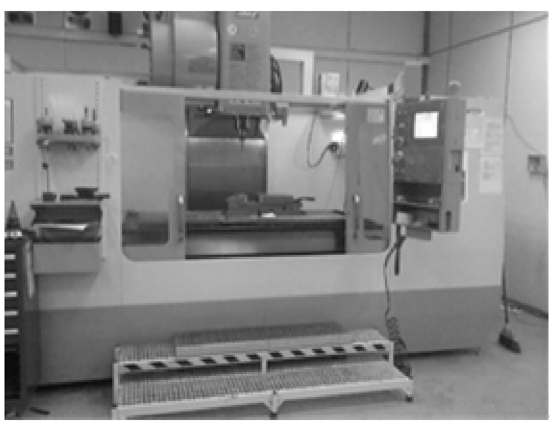


Figure 2: 90^0 tool holder of CNC milling machine

Table 1: Chemical composition of aluminium alloys 6061-T6 workpiece

Composition	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
Wt %	95.8-98.6	0.04-0.35	0.15-0.4	Max 0.7	0.8-1.2	Max 0.15	0.4-0.8	Max 0.15	Max 0.25

Table 2: Design parameters for aluminium alloys (AA6061-T6) milling

Cutting Speed (m/min)	Feed Rate (mm/rev)	Axial Depth (mm)	Radial Depth (mm)
140	0.15	0.1	5
140	0.15	0.15	3.5
100	0.15	0.15	5
140	0.15	0.15	3.5
180	0.15	0.2	3.5
180	0.15	0.15	2
100	0.2	0.15	3.5
140	0.15	0.15	3.5
180	0.15	0.15	5
100	0.15	0.2	3.5
140	0.2	0.1	3.5
180	0.1	0.15	3.5
140	0.15	0.2	2
180	0.15	0.1	3.5
140	0.1	0.15	2
140	0.15	0.2	5
100	0.15	0.1	3.5
140	0.2	0.15	2
100	0.15	0.15	2
140	0.2	0.15	5
140	0.1	0.1	3.5
140	0.2	0.2	3.5
140	0.15	0.1	2
100	0.1	0.15	3.5
180	0.2	0.15	3.5
140	0.1	0.2	3.5
140	0.1	0.15	5

4. Results and Discussion

After conducting the first pass (one pass is equal to 90 mm length) of the 27 cutting experiments, the surface roughness readings are used to find the parameters appearing in the postulated first-order and second-order model (Equation 1 & 2). In order to calculate these parameters, the least square method is used with the aid of Minitab. The first-order and second order linear equation used to predict the surface roughness is expressed as:

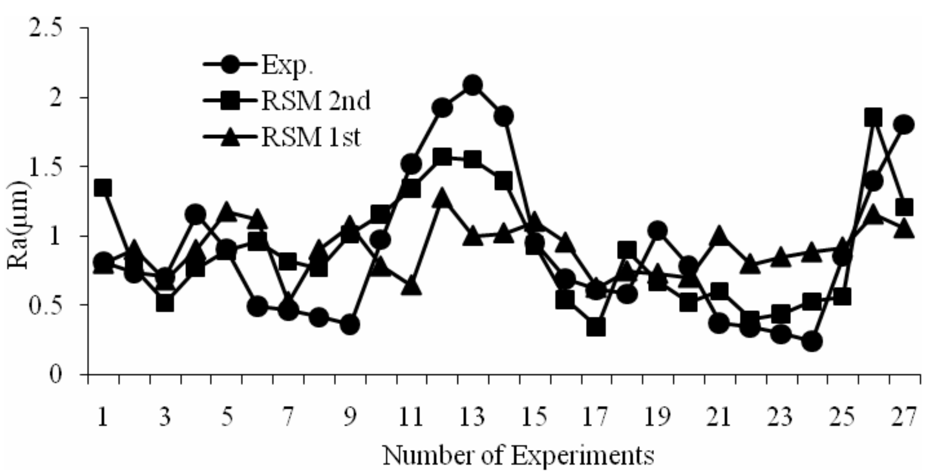
$$R_a = 0.5764 + 0.0049C_{speed} + 47.69f + 58.45a_{depth} + 1.08r_{depth} + 40.37f^2 + 7217a_{depth}^2 \quad (4)$$

$$R_a = 2.83 + 0.0511C_{speed} + 47.69f + 58.45a_{depth} + 1.08r_{depth} + 40.37f^2 + 72.17a_{depth}^2 + 0.0094r_{depth}^2 - 0.162C_{speed} \times f - 0.1652C_{speed} \times a_{depth} - 220f \times a_{depth} - 2.18f \times r_{depth} - 6.38a_{depth} \times r_{depth} \quad (5)$$

where C_{speed}, f, a_{depth} and r_{depth} are the cutting speed, feed rate, axial depth and radial depth respectively

Generally, reduction of cutting speed, axial depth of cut caused the larger surface roughness. On the other hand, the increase in feed rate and radial depth caused slightly reduction of surface roughness. The feed rate is the most dominant factors on the surface roughness, followed by the axial depth, cutting speed and radial depth respectively. Hence, a better surface roughness is obtained with the combination of low cutting speed and axial depth, high feed rate and radial depth. Similar to the first-order model, by examining the coefficients of the second-order terms, the feedrate (f) has the most dominant effect on the surface roughness. After examining the experimental data, it can be seen that the contribution of cutting speed (C_{speed}) is the least significant. Also, owing to the P-value of interaction is 0.161 (>0.05), one can easily deduce that the interactions of distinct design variables are not significant. In other words, the most dominant design variable f and a_{depth} has minimum interaction with others in the current context. As seen from Fig. 3, the predicted surface roughness using the second order RSM model is closely match with the experimental results. It exhibits the better agreement as compared to those from the first-order RSM model.

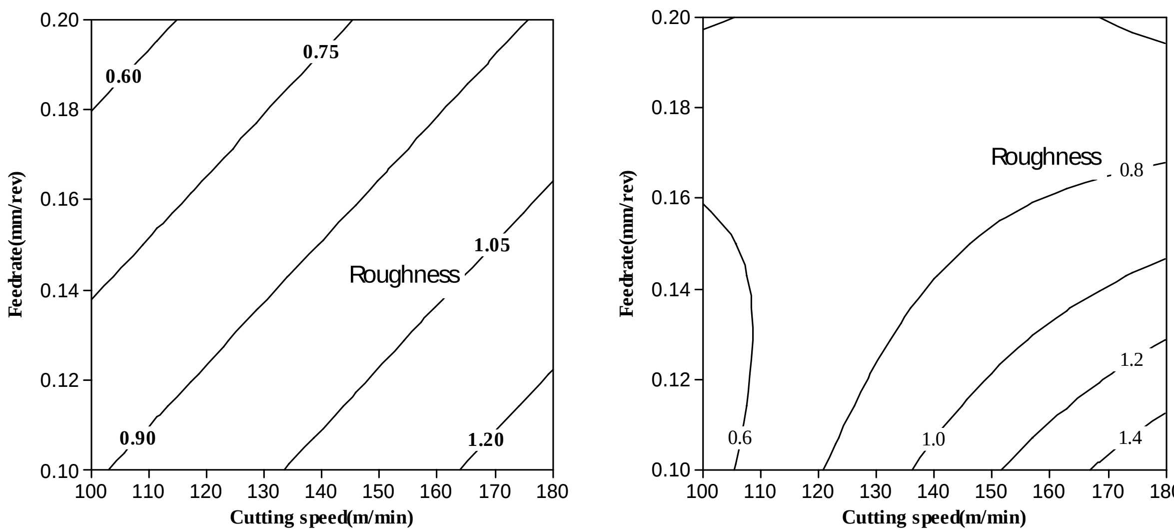
Figure 3: Comparison between the experimental and predicted results



Feed rate versus cutting speed contour plotted for first-and second-order model are shown in Fig.4. The axial and radial depth fixed at middle point. Combination of high cutting speed and low federate produce rough surface. It is clearly shown that the relationship between the surface roughness and design variables.

The adequacy of the first and second order model was verified using the analysis of variance (ANOVA) as shown in Table 3 and Table 4. At a level of confidence of 95%, the model was checked for its adequacy. As shown in Table 3 and 4, P value of 0.351 and 0.36 (> 0.05) is not significant with the lack-of fit and F-statistic is 2.27 and 2.14. This implies that the model could fit and it is adequate.

Figure 4: 11: Surface roughness contours in the cutting speed-feed rate plane for axial depth 0.15mm and 3.5 mm (a) first-order; (b) second-order model



(a) (b)

Table 3: Analysis of variance for first-order equation

Source	Degree of Freedom	Sum of Squares	Mean Squares	*F-ratio*	*P-value*
Regression	4	0.9309	0.2327	0.78	0.552
Linear	4	0.9309	0.2327	0.78	0.552
Residual Error	22	6.5937	0.2997		
Lack-of-Fit	20	6.3151	0.3158	2.27	0.351
Pure Error	2	0.2786	0.1393		
Total	26	7.5246			

Table 4: Analysis of variance for second-order equation

Source	Degree of Freedom	Sum of Squares	Mean Squares	*F-ratio*	*P-value*
Regression	14	4.262	0.3044	1.12	0.427
Linear	4	0.931	0.23271	0.86	0.517
Square	4	0.224	0.05589	0.21	0.93
Interaction	6	3.107	0.51787	1.9	0.161
Residual Error	12	3.263	0.27191		
Lack-of-Fit	10	2.984	0.29843	2.14	0.36
Pure Error	2	0.279	0.13932		
Total	26	7.525			

6. Conclusions

RSM found successful technique to perform trend analysis of surface roughness with respect to various combinations of design variables (cutting speed, feed rate, axial depth and radial depth). The first-and second–order models found to be adequately representing the surface roughness with experimental results. RSM model reveal that feed rate is the most significant design variable to predict the surface roughness response as compared to others. Second-order model found to be no interaction between the variables. With the model equations obtained, a designer can subsequently select the best combination of design variables for achieving optimum surface roughness. This eventually reduces the machining time and save the cutting tools.

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