Development of Response Surface Model to Predict the Surface Roughness During Milling of Aluminium Alloy

Chockaligam Palanisamy, Jasdeep Singh Amardip Singh, Natarajan Chinnasamy

***Abstract*— Milling of Aluminium T6-6061 structures is a complex and challenging process due to the difficulties in finding the optimum milling process control parameters for achieving the desirable surface roughness. The optimum parameters selection generally is based on the skill and cost consuming trial and error runs. An attempt was hence made to systematically investigate the influencing process control parameters on the surface roughness of Aluminum 6061-T6 by Response Surface Methodology (RSM). Mathematical models were developed to show the relationship between process variables and their responses that will help to select process control variables effectively, to achieve the desired results. It has been found that spindle feed and spindle speeds have highest effect on the roughness on milling of aluminium T6-6061.**

***Index Terms*—Aluminium 6061, Milling, Surface Roughness, RSM.**

1) Introduction

In a manufacturing operation, produce components with high quality is a priority. There are many dilemmas which manufacturers face everywhere in controlling the process factor parameters. It is vital for the optimum parameters to be researched in order to improve the cutting performance, minimize the total cost in machining and also to improve the process efficiency of machining [1]. Two of the most critical yield parameters in any machining process is the surface finish and machining timing. Surface roughness regularly abbreviated to roughness, is a measure of the finely dispersed surface irregularities. Surface roughness of a machined item assumes a huge part in deciding the nature of the item in today's assembling industry. The setting up of machining parameters depends unequivocally on the operators experience. It is hard to use the most elevated execution of a machine inferable from their being an excess of movable machining parameters. The impacts of different parameters of milling processing process have been explored [2]. Aluminum is a gleaming white, versatile ductile metallic substance component found in the earth and it is utilized commercially in many products [3]. It is erosion safe and has high electrical conductivity, which makes it the second most generally utilized metal after steel [4]. Milling is a kind of machining process. RSM is a combination of statistical and mathematical processes. It is vital in representing and explaining complex effects of variables that are dependent on the factor response. The RSM method represents mathematical connection between numerous process variables and reactions. RSM is able to resolve optimization predicaments of a reaction inconstant within scope of a study. Nonetheless, the resolution of optimization relies highly on suitability of choice of Design of Experiment (DOE) [5]. This research work is planned to perceive the idea and interrelationship among the reaction variables amid the processing procedure and its control elements keeping in mind the end goal to know the surface roughness. Furthermore, design of experiment techniques will also be implemented in order to form mathematical models. These models will then be used for prediction of responses and optimization.

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2) Materials and Methods

The milling process of the was performed using Master CNC 10HVA milling. The milling was done with high speed steel end mill of 6mm diameter on 160 mm x 100 mm x 10 mm material [6]. Aluminium T6-6061 and high speed steel end milling cutter are selected as a workpiece material and cutter due to its commercial use in the industry [7]. Fig. 1 shows the experimental setup of the milling process.

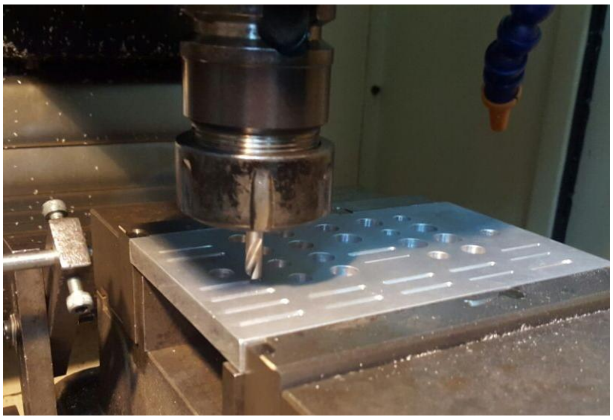


Figure 1 Experimental setup

The table 1 shows the selected variable process parameters are such as tool feed, the depth of cut, and spindle speed and their levels. The designated design matrix is a composite three variable design matrix. The middle (0) level comprising the center points holds all milling variables. On the other hand, the single milling factor at each of its lowest value

(-1.68179) or its peak value (+1.68179) are represented. Table 2 presents the design matrix and the response value.

Table 1 Process parameters and their levels

Parameter	levels				
	+1.68	**+1**	**0**	**-1**	**-1.68**
Speed (rpm)	9400	8000	6000	4000	2700
Feed (mm/min)	94	80	60	40	26
Depth of cut (mm)	1.8	1.5	1	0.5	0.2

Table 2 Design parameters and measured roughness

Standard Order	Run Order	Spindle Speed,S (rpm)	Spindle Feed,F (mm/min)	Depth of Cut, D (mm)	Surface Roughness (μm)
1	4	4000	40	0.5	5.35
2	10	8000	40	0.5	2.195
3	14	4000	80	0.5	11.26
4	17	8000	80	0.5	9.94
5	16	4000	40	1.5	6.43
6	11	8000	40	1.5	2.20
7	2	4000	80	1.5	11.30
8	6	8000	80	1.5	10.20
9	7	2700	60	1	9.56
10	1	9400	60	1	3.71
11	8	6000	26	1	1.93
12	13	6000	94	1	11.78
13	15	6000	60	0.2	4.05
14	5	6000	60	1.8	6.95
15	12	6000	60	1	4.80
16	9	6000	60	1	5.42
17	3	6000	60	1	4.93

3) Results and Discussion

The milling parameters and the results data were analyzed using Minitab 16, mathematical and statistical software to determine the coefficient and the mathematical modeling [8].The response function representing surface roughness expressed as X =*F*(S, F, D). Equation (1) expresses the relationship chosen being a second-degree response surface.

$$X = b_0 + b_1 S + b_2 F + b_3 D + b_{11} S^2 + b_{22} F^2 + b_{33} D^2 + b_{12} SF + b_{13} SD + b_{23} FD \quad (1)$$

1) Analyzing the Adequacy of the Model

In order to denote a significant model term, "Probability > F" should have value of less than 0.0500. Based on this circumstance, it can be seen that the significant model terms are Speed, Feed, Speed^2 and Feed^2. Considerations that have to be taken on include model reduction, response transformation, and outliers [9]. The design space can be navigated then by using the model shown in equation (2).

$$\text{Surface Roughness} = 19.2899 - (0.00385*S) - (0.180*F) - (0.777298*D) + 1.932 \times 10^{-7} *(S^2) + 0.00213*(F^2) + 1.479*(D^2) + 1.539 \times 10^{-5} *(S*F) - 1.14 \times 10^{-4} *(S*D) - 0.00958*(F*D) \quad (2)$$

Table 3 Analysis of variance table

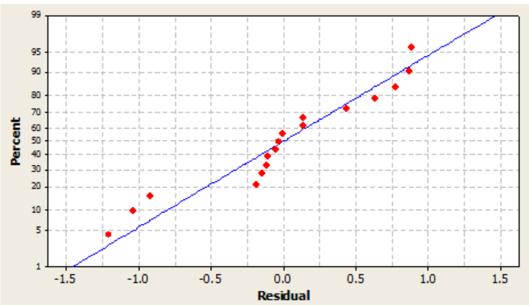
Source	Sum of Squares	DF	Mean Squares	F Value	p-value Prob > F	Significant
Model	182.16	9	20.24	22.67	0.000	
S-Speed	28.37	1	28.37	31.77	0.001	Significant
F-Feed	136.17	1	136.17	152.49	0.000	Significant
D-Depth	2.904	1	2.904	3.25	0.114	
S^2	3.186	1	6.733	7.54	0.029	Significant
F^2	6.788	1	8.16	9.13	0.019	Significant
D^2	1.541	1	1.54	1.73	0.230	
S*F	3.031	1	3.03	3.39	0.108	
S*D	0.104	1	0.10	0.12	0.743	
F*D	0.073	1	0.07	0.08	0.783	
Residual	6.251	7	0.89			
Lack of Fit	6.035	5	1.21	11.20	0.084	Not Significant
Pure Error	0.216	2	0.11			
Total	188.46	16				

2) Analyzing the Coefficient Significance

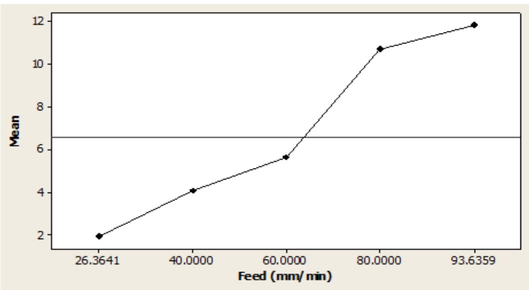
Values of the regression coefficient delineate an awareness to what extend control parameter have an effect on the responses significantly. Irrelevant coefficient can be dropped or canceled out as they are linked without having great or significant effect on the model's accuracy. Referring to Table 3, there are four significant factors which are Speed, Feed, $Speed^2$ and $Feed^2$. The model for surface roughness was developed and is shown in equation (3). By referring to Fig. 2, we can observe the normal probability plot of the residuals where by looking at the graph, we can identify if the residuals are normally distributed. It should follow a straight line if it is normally distributed. From the graph; the values are quite close to the linear line with a R-squared value of 92.42% that would mean that the predicted values are 92.42% closer to the actual value. The value is high and close to unity. In this case, the Adjusted R-squared value is used compared to the original value because the original R-squared value will always increase if more terms are added in the model. Therefore, Adjusted R-squared is preferable [10].

$$\text{Surface Roughness}=19.289-(0.00385*S)-(0.180*F)+1.932\times 10^{-7}*(S^2)+0.00213*(F^2) \quad (3)$$

The main effect plot using data means for surface is showed in Fig. 2 (a) where the effect of feed on surface roughness can be observed. As the milling parameter for speed and depth of cut are 6000rpm and 1mm respectively, the surface roughness value is the highest at 11.780µm at the highest feed point of 93.6359 mm/min. The lowest feed point of 26.3641 mm/min provides the lowest surface roughness value of 1.934 µm. As the spindle feed value increases, we can see that the surface roughness value increases too. By referring to Fig. 2(b), the increment in the value of the spindle speed can be seen to cause the decrement in the value of the surface roughness for the speed milling parameter. As can be seen from the figure, the highest speed is at 9363.59 rpm which gives the mean roughness at 3.711 µm with the feed of 60mm/min and depth of 1mm. However, the lowest surface roughness value throughout the experiment is 1.934 µm which is at the cut depth of 1mm, speed of 6000 rpm and feed of 26 mm/min. The lowest spindle speed of 2636.41 rpm has the surface roughness value of 9.56 µm. However, the highest surface roughness value is at 11.78 µm with the spindle speed of 6000 rpm. The mean surface roughness value however increases between the speed of 6000 rpm and 8000 rpm. This implies speed is not most considerable parameter in this experiment.



(a)

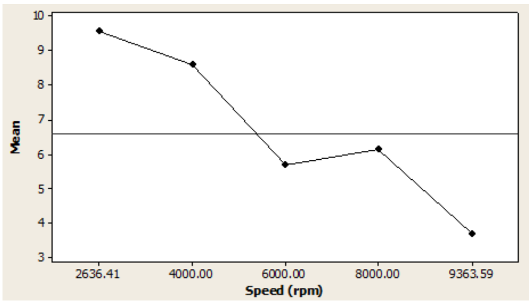


(b)

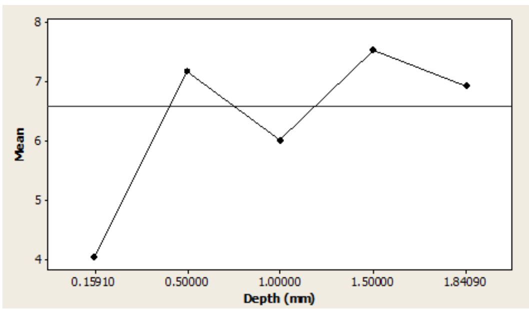
Figure 2 (a) Normal probability plot of residuals (b) Effects Plot for roughness for feed.

Fig. 3(b) below shows the effects plot for roughness using data means for the depth of cut. From the figure, we can see that the surface roughness value increases from the depth 0.1591 mm and 0.5 mm, however decreases when the depth is at 1mm and then it increases again when the depth is at 1.5 mm but however decreases when the depth is at the highest of 1.84090mm. At the lowest value depth of 0.159 mm, it has the surface roughness value of 4.048µm while at the highest value depth of 1.8409 mm, it has the surface roughness value of 6.946 µm. From all this observations, it is clear that the depth of cut is not a significant parameter in this experiment in measuring surface roughness. The effect of the spindle speed and feed based on the surface roughness is very obviously seen based on Fig. 2 (b), Fig. 3 (a). In this period, where the feed decreases and the speed increases, the surface roughness value increases. We can also conclude that the spindle feed is the most significant parameter followed by the spindle speed and then the depth of cut.

The interaction effect of speed and feed on the roughness with hold values of depth of cut at 1mm is as graphically shown in the form of contour plot as Fig. 4 (a). It is seen that the surface roughness values increments as the spindle feed increments. On the other hand, the surface roughness value reduces as the spindle speed increases. From the plot it is clearer to see the interaction between these parameters. The surface roughness increment moves towards the top left corner area. The darker the green color indicates an increase



(a)

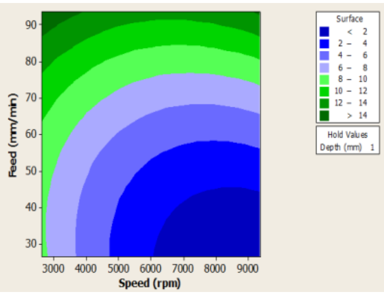


(b)

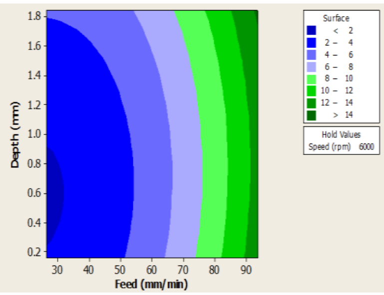
Figure 3 (a) Effects plot for roughness for Speed (b) Effects plot for roughness for cut depth.

in surface roughness. Roughness of 11.78 µm is the highest at the feed of 94 mm/min with the spindle speed of 6000 rpm while lowest at the feed of 26 mm/min with the spindle speed of 6000 rpm at 1.934 µm. At the highest spindle speed of 9363.59 rpm, the surface roughness is 3.711 µm while at the lowest spindle speed of 2636.41 rpm, the surface roughness is 9.563 µm. This pattern is normal on the grounds with increasing cutting feed. This is because when the feed increases, more heat, interference and friction occurs. This will allow more chips to be kept between the work-piece and tool interface. This will bring about a poorer surface completion. This has less intrusion between the workpiece-tool and instrument chips which will allow a decrease in friction between the workpiece-tool interface.

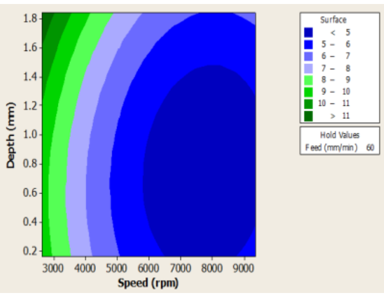
Fig. 4 (b) illustrates the contour plot for interaction effect of depth of cut and spindle feed on surface roughness with hold value of speed at 6000 rpm respectively. It can also clearly be seen that as feed increases, the surface roughness value increases. From the plot, it can be seen that the surface roughness increment moves towards the right side area. The darker the green color indicates an increase in surface roughness. The 1 mm depth of cut and feed of 94 mm/min



(a)



(b)



(c)

Figure 4 Contour graphs for surface roughness (a) effect of feed and speed (b) effect of spindle feed and depth of cut (c) effect of speed and depth of cut

gives the largest value of surface while lowest at the feed of 26 mm/min and depth of cut of 1mm also. At the highest depth of cut of 1.84090 mm, the surface roughness is 6.946 µm while at the lowest depth of cut of 0.159 mm, the surface roughness is 4.048µm. With all this it can be clearly seen that the depth of cut is insignificant in this experiment. Although there is some increase on the surface roughness as the depth of cut increases, it depends mainly on the other process parameters as well. This increase is because with more width of contact between the cutting tool and the material, it increases the friction between the tool and workpiece. This would lead to interference in the milling operation. Poor surface quality will be resulted in this as more energy will be used during the milling operation.

Fig. 4 (c) illustrates the contour plot for interaction effect of depth of cut and spindle speed on surface roughness with hold value of feed at 60mm/min respectively. The decrement in the surface roughness value is clearly seen to be due to the increment of the spindle speed. Fig. 4 (c) shows the surface roughness increment moves towards the top left corner area from the contour plot. The darker the green color indicates an increase in surface roughness. Besides that, it can also be seen with the dark blue color that surface roughness value of 1.934 µm is lowest which is at 1 mm. With the declining value of spindle speed, the increment of depth will cause the surface roughness value to increase. At the lowest spindle speed of 2636.4 rpm and depth of cut of 1 mm, the surface roughness is 9.563 µm while at the highest spindle speed of 9363.59 rpm and depth of cut of 1mm, the surface roughness is 3.711 µm. The outcome is normal on the grounds that at low spindle speed. This is because the irregular chip shaped which is kept in the tool interface produces high friction between the cutting tool and work-piece. This high friction prompts intrusions amid cutting operations, high temperature of heat, more energy, high force in machining and prompting a poor surface quality. When the chips formed are consistent with the increasing spindle speed, they make less contact with the tool interface. This results in low coefficient of friction and higher surface roughness finish.

4) CONCLUSION

Based on the result of this research and analysis, in order to establish response surface model to be used in predicting the surface roughness inside the viable sector of control parameters for milling of aluminium alloy, the five level factorial system or approach could be engaged efficiently. Besides that, the cause and the result of process parameters on response analyzed efficiently. Additionally the contour plot for responses generated in order to display the interaction outcomes of disparate process parameters. The response surface modeling for surface roughness with an equation of, Surface Roughness = 19.2899 – (0.00385*S) – (0.180*F) + 1.932 x 10^{-7} *(S^2) + 0.00213*(F^2), is developed. Lower surface roughness value will be obtained with the increase of spindle speed as well as with reduced spindle feed. The surface roughness value of the milled aluminium alloy can also be reduced with the reduction of the spindle feed as well as the depth of cut.

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