Optimization of milling process parameters of aluminium alloy LM6 using response surface methodology

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Abstract. This paper discusses the use of response surface methodology (RSM) for maximizing Metal Removal Rate (MRR) and minimizing Surface Roughness (Ra) in machining LM6 alloy material. The levels of three machining parameters spindle speed, feed rate and depth of cut are optimized during end milling operation. RSM is used for this experimentation. The regression models are developed and effect of each parameter on MRR and Ra is identified through the regression models. The results are analyzed through response surface and contour plots. The significant parameters are identified through Analysis of Variance (ANOVA) for MRR and Ra; all three parameters are significant for MRR, whereas spindle speed and feed rate are significant for Ra. Response surface optimization shows that the milling parameters are 2550RPM, 0.202mm/rev and 1mm for spindle speed, feed rate and depth of cut respectively. The maximum value for MRR is 0.043kg/min and that for surface roughness is 2.007μm at optimal parameter levels.

Keywords: Aluminium alloy LM6, metal removal rate, surface roughness, response surface methodology and optimization.

1. Introduction

The alloying elements are added to obtain requisite properties in pure metals. The alloying elements are in lower percentages to improve hardness or strength and in larger percentages to obtain special properties [1]. Although a number of alloys of aluminum are in use, the most versatile alloys are the aluminium-silicon alloys, especially for automotive applications. In particular, aluminium with 11.6% silicon alloy (Al-11.6% Si alloy) is the most widely used aluminium cast alloy. Al-11.6% Si is an eutectic alloy having lowest melting point (liquidus temperature), and this eutectic alloy was selected for the experimentation [2][3][4].

The selection of efficient machining parameters is of great concern in the industry where economy of machining operations plays a key role in the competitive market. Thus, there is a need for optimization of the machining parameters. Milling machines are used for a variety of complicated cutting operations –from slot cutting, threading to drilling etc. This work aim to improve the quality of the machined product and...
thereby to increase its reliability which finally helps in adding value to the products manufactured [5][6]. Increase in Metal Removal Rate (MRR) during machining is indicate the improvement in productivity. Decrease in surface roughness (Ra) is considered as the quality improvement in the machined product. MRR and Ra are influenced by various parameters such as properties of the work and tool material, coolant, operator skill, environmental conditions, cutter parameters, cutting parameters such as cutting speed, feed and depth of cut etc.

During milling operation, some of the parameters are controlled by the operator or experimenter; these are called controllable parameters. Optimization of these controllable parameters levels can be made possible through statistical methods [7]. RSM is one such statistical tool which reduce the cost of expensive analytical method and three-dimensional contour plots of RSM help to visualize the responses in a very effective manner. ANOVA evaluates the effect of input parameters on the responses. F-test is performed to determine whether parameters are significant or not [8][9].

2. Materials and Experimentation

Alloy used in this experimentation is aluminium alloy LM6. Composition of the LM6 is shown in Table 1.

| Element | Al | Si | Cu | Mg | Fe | Mn | Ni | Zn | Pb | Sn | Ti |
|---------|----|----|----|----|----|----|----|----|----|----|----|
| Wt. %   | 86.35 | 11.6 | 0.1 | 0.1 | 0.6 | 0.5 | 0.1 | 0.1 | 0.1 | 0.05 | 0.2 |

The work pieces were in the form of rectangular blocks of size approximately 126 X 50 X 38(mm). Milling operation was performed on the work pieces by varying the controllable parameter levels. Vertical machining center, MCV-300, is highly efficient and space saving machining center with specially designed features that is suitable of machining small components.

As per the recommendations from the cutting tool maker, the levels of the parameters are shown in Table 2. Once the levels are defined, MINITAB software is used to create the Central Composite Design (CCD) of three continuous factors with no blocking effect and the design matrix is shown in the Table 3. MRR is calculated by recording the weight of material removed in each cycle and the machining time. Surface roughness is measured by using TR200 Surface roughness tester. MRR and Ra values are tabulated as per design matrix and shown in the Table 3.
Table 3. Design matrix with MRR and Ra values

| Standard Order | Run Order | Spindle Speed | Feed Rate | Depth of Cut | MRR (kg/min) | Ra (μm) |
|----------------|-----------|---------------|-----------|--------------|--------------|---------|
| 1              | 1         | 1529.454      | 0.24054   | 0.362159     | 0.0193       | 3.23    |
| 2              | 2         | 2290.546      | 0.24054   | 0.362159     | 0.0214       | 2.84    |
| 3              | 3         | 1529.454      | 0.35946   | 0.362159     | 0.0233       | 5.22    |
| 4              | 4         | 2290.546      | 0.35946   | 0.362159     | 0.0243       | 4.82    |
| 5              | 5         | 1529.454      | 0.24054   | 0.837841     | 0.0340       | 3.23    |
| 6              | 6         | 2290.546      | 0.24054   | 0.837841     | 0.0365       | 2.84    |
| 7              | 7         | 1529.454      | 0.35946   | 0.837841     | 0.0369       | 5.22    |
| 8              | 8         | 2290.546      | 0.35946   | 0.837841     | 0.0429       | 4.83    |
| 9              | 9         | 1270          | 0.3       | 0.6          | 0.0269       | 4.36    |
| 10             | 10        | 2550          | 0.3       | 0.6          | 0.0322       | 3.71    |
| 11             | 11        | 1910          | 0.2       | 0.6          | 0.0236       | 2.36    |
| 12             | 12        | 1910          | 0.4       | 0.6          | 0.0364       | 5.69    |
| 13             | 13        | 1910          | 0.3       | 0.2          | 0.0157       | 4.03    |
| 14             | 14        | 1910          | 0.3       | 1            | 0.0426       | 4.19    |
| 15             | 15        | 1910          | 0.3       | 0.6          | 0.0289       | 4.16    |
| 16             | 16        | 1910          | 0.3       | 0.6          | 0.0284       | 4.02    |
| 17             | 17        | 1910          | 0.3       | 0.6          | 0.0291       | 4.01    |
| 18             | 18        | 1910          | 0.3       | 0.6          | 0.0286       | 4.18    |
| 19             | 19        | 1910          | 0.3       | 0.6          | 0.0282       | 4.19    |
| 20             | 20        | 1910          | 0.3       | 0.6          | 0.0292       | 4.03    |

3. Statistical analysis for MRR

The data points in Figure 1, (first plot) are along the normal line and having negligible outliers, which infer that data is normally distributed. Data points in second plot do not show any trend which indicates that RSM model is a good-fit with given dataset and the residual is independent of the fitted value. The frequency histogram is shown in the third plot and fourth plot indicates the non-significance of run order.

Detailed statistics on MRR are obtained from the ANOVA summary Table 4. The p-value for all the parameters are less than 0.05 at 95% confidence interval. The p-values of square and interaction terms are more than 0.05 and hence these terms may be ignored during optimization of MRR. ANOVA on MRR shows the significant for linear (p-value < 0.05) and not significant for square and interactions on MRR model. The optimization equation for MRR in terms of variables and its interaction effect is obtained by Eq. (1). It is also clear from the coefficients in Eq. (1) that feed rate and depth of cut are more influential parameters on MRR. R² – value, which is coefficient of determination, is close to 100%, which is desirable.

\[
MRR = 0.0295 - 0.000013s - 0.0750 f + 0.0084d + 0.1 \times 10^{-6} s^2 + 0.1391 f \times f + 0.00338d \times d \\
+ 0.000013s \times f + 0.000007s \times d + 0.0212f \times d
\]  

(1)
Table 4. ANOVA for MRR

| Source         | DF | Adj SS      | Adj MS   | F-Value | P-Value |
|----------------|----|-------------|----------|---------|---------|
| Model          | 9  | 0.000987    | 0.000110 | 76.50   | 0.000   |
| Linear         | 3  | 0.000977    | 0.000326 | 227.20  | 0.000   |
| s              | 1  | 0.000031    | 0.000031 | 21.49   | 0.001   |
| f              | 1  | 0.000104    | 0.000104 | 72.70   | 0.000   |
| d              | 1  | 0.000842    | 0.000842 | 587.40  | 0.000   |
| Square         | 3  | 0.000005    | 0.000002 | 1.13    | 0.383   |
| s*s            | 1  | 0.000002    | 0.000002 | 1.11    | 0.316   |
| f*f            | 1  | 0.000003    | 0.000003 | 2.43    | 0.150   |
| d*d            | 1  | 0.000001    | 0.000001 | 0.37    | 0.558   |
| 2-Way Interaction | 3  | 0.000005    | 0.000002 | 1.18    | 0.365   |
| s*f            | 1  | 0.000001    | 0.000001 | 0.50    | 0.495   |
| s*d            | 1  | 0.000004    | 0.000004 | 2.54    | 0.142   |
| f*d            | 1  | 0.000001    | 0.000001 | 0.50    | 0.495   |
| Error          | 10 | 0.000014    | 0.000001 |         |         |
| Total          | 19 | 0.001001    |          |         |         |
| R²             |    | 98.57%      |          |         |         |

3.1 Main effect plots for MRR

Figure 2 is generated from Minitab and depicts the effect of each parameter on MRR. It observed from the graph that as spindle speed, feed rate and depth of cut increase, MRR is increased. The depth of cut has a predominant role on MRR.
3.2 Response Surface Plots and Contour Plots of MRR

Response surface plots are three-dimensional graphs which show simultaneous effect of two variables on a response keeping other variables constant. Contour plots are two-dimensional graphs generated from the response surface plots. Surface plots (Fig.3) show the effect of variables on MRR; the graph shows an increasing trend in MRR for increase in spindle speed, feed and depth of cut. The contour graphs depict the optimum parameters values on responses.

Figure 3. Surface plots on MRR
Figure 4. Contour graph of MRR

Figure 4a is the contour plot of MRR with the variables – feed rate and depth of cut at a constant spindle speed of 1919 RPM. The plot shows the maximum value of MRR which is more than 0.045 kg/min. Maximum value of MRR is also more than 0.045 kg/min for depth of cut and spindle speed shown in contour plot of Figure 4b. Figure 4c shows the maximum value of MRR which is more than 0.0375 kg/min at the maximum values of feed rate and spindle speed.

4. Statistical analysis for Ra

Residual plot of Ra is shown in Figure 5. The figure reveals the normality of the data, without any trend in residual. This residual is not following any trend with run order and hence there is no dependence of residual on the run order.

Figure 5. Residual plots for Ra
Table 5 gives the ANOVA summary of Ra. The p-values of spindle speed and feed are less than 0.05; these parameters are significant parameters and depth of cut is not significant for Ra. The term $s \times s$ is also significant. $R^2$ value is close to 100%, which is desirable.

| Source            | DF | Adj SS  | Adj MS  | F-Value | P-Value |
|-------------------|----|---------|---------|---------|---------|
| Model             | 9  | 13.9930 | 1.5548  | 332.64  | 0.000   |
| Linear            | 3  | 13.9698 | 4.6566  | 996.28  | 0.000   |
| $s$               | 1  | 0.5193  | 0.5193  | 111.11  | 0.000   |
| $f$               | 1  | 13.4447 | 13.4447 | 2876.50 | 0.000   |
| $d$               | 1  | 0.0057  | 0.0057  | 1.22    | 0.295   |
| Square            | 3  | 0.0232  | 0.0077  | 1.65    | 0.239   |
| $s^2$             | 1  | 0.0111  | 0.0111  | 2.37    | 0.154   |
| $f^2$             | 1  | 0.0141  | 0.0141  | 3.02    | 0.113   |
| $d^2$             | 1  | 0.0000  | 0.0000  | 0.00    | 0.947   |
| 2-Way Interaction | 3  | 0.0000  | 0.0000  | 0.00    | 1.000   |
| $s \times f$      | 1  | 0.0000  | 0.0000  | 0.00    | 0.960   |
| $s \times d$      | 1  | 0.0000  | 0.0000  | 0.00    | 0.960   |
| $f \times d$      | 1  | 0.0000  | 0.0000  | 0.00    | 0.960   |
| Error             | 10 | 0.0467  | 0.0047  |         |         |
| Lack-of-Fit       | 5  | 0.0093  | 0.0019  | 0.25    | 0.925   |
| Pure Error        | 5  | 0.0375  | 0.0075  |         |         |
| Total             | 19 | 14.0397 |         |         |         |
| $R^2$             |    | 99.67%  |         |         |         |

4.1 Main effect plots for Ra

Effect of each parameter on Ra is shown in the Figure 6. The main effect plots reveal that higher the spindle speed, lower the Ra value. As the feed rate increases Ra value also increases and depth of cut is not contributing on Ra. The coefficients in the regression equation (Eq. 2) reveal the effect of feed rate and depth of cut, which is much higher than spindle speed.

$$Ra = -1.48 + 0.000228s + 22.05f + 0.059d - 0.000003s \times s - 8.85f \times f - 0.022d \times d - 0.00006s \times f + 0.000014s \times d + 0.09f \times d$$

(2)
4.2 Response Surface Plots and Contour Plots of Ra

The response surface plots on Ra shows the 3-D surfaces on two variables. Figure 7a to Figure 7c are the surface plots of Ra on two variables. Figure 7a is the surface plot for depth of cut and feed rate on hold value of spindle speed 1910RPM. This graph reveals the linearity of Ra with variables. Figure 7b shows surface plots for depth of cut and spindle speed at hold value of feed rate 0.3mm/rev; this shows the almost linearity of Ra. Figure 7c is the surface plot for feed rate and spindle speed at hold value of depth of cut 0.6 mm. The surface plot shows the almost linear behavior of Ra with the variables.
Variation of Ra values with two parameters are shown in Figure 8a, Figure 8b and Figure 8c. From Figure 8a shows the maximum Ra value (Ra > 5.5) at feed rate: 0.4mm/rev and depth of cut 1mm. From Figure 8b indicates maximum Ra value (Ra > 4.3) at spindle speed: 1500 RPM and depth of cut 1mm. The graph (Figure 8c) shows the maximum Ra value (Ra > 5) at spindle speed: 1500 RPM and feed rate: 0.4 mm/rev.

4.3 Optimized solution

The parameters are optimized using the Minitab response optimizer. Response optimizer is used to identify the combination of input parameters settings that optimize a single response or a set of responses.
Figure 9 shows the optimal parameter values to maximize MRR and minimize Ra. The optimum values are: spindle speed- 2550RPM, feed rate- 0.202mm/rev and depth of cut- 1mm. The maximum MRR is 0.043kg/min and minimum Ra is 2.007μm with individual desirability d =1mm at optimal parameter levels. The confirmation experiments have been carried out to re-confirm the same.

5. Conclusion
Application of RSM on aluminium alloy LM6 specimens is carried out for milling operation. A regression model is developed for MRR and surface roughness to investigate the influence of spindle speed, feed rate and depth of cut. The analysis of the results is carried out using Minitab software. From the response surface analysis it is found that, although all parameters significantly contribute to MRR, the feed rate has the largest influence. Whereas, for the surface roughness, only spindle speed and feed rate are found as significant. The 3D surface plot and contour plot show the effect of two parameters at a time on MRR and surface roughness. The optimal parameter levels are obtained from Minitab to maximize MRR and minimize surface roughness during machining. The optimal levels machining parameters are 2550RPM, 0.202mm/rev and 1mm for spindle speed, feed rate and depth of cut respectively. The maximum MRR is 0.043kg/min and surface roughness is 2.007μm at optimal parameter levels. The confirmation experiments have been carried out to validate the results.

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