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Optimization of Machining Parameters for Surface Roughness in End Milling of Magnesium AM60 Alloy

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Abstract

Objective: The present work is aimed to find an optimum combination of cutting parameters to achieve low surface roughness in end milling of magnesium AM60 with TiN coated carbide tool under dry conditions. **Methods:** Design of Experiments (DOE) with Response Surface Methodology (RSM) using Box-Behnken design and the regression equations are used to find the optimal combinations of cutting parameters to achieve low surface roughness. The developed RSM model was experienced through Analysis of Variance (ANOVA). An ANOVA analysis was performed to indicate the control of three machining parameters on the surface roughness. **Findings:** The cutting parameters assessed were spindle speed, depth of cut and feed rate have the greatest effect on the success of the milling operation. Confirmation experiments with the optimum combinations of cutting parameters were carried out in order to explain the efficiency of the response surface design concepts. From ANOVA results, the feed rate was found to be most significant factor affects surface roughness of milled surface. Feed rate, depth of cut and spindle speed affects the surface roughness by 76.18%, 2.94% and 1.99% respectively. It can be fulfilled that RSM method is effective and efficient method to optimize milling parameters for low surface roughness. **Applications:** Magnesium (Mg) is now emerging as a popular metal for replacing Aluminum (Al) and finding applications in automobile and aerospace industries where fine finishing of the machined component is ultimate requirements to achieve a product quality.

Keywords: End Milling, Magnesium, Response Surface Methodology, Surface Roughness

1. Introduction

Magnesium is the lightest of all the engineering metal with the density of 1.74 g/cm^3. It is 35% lighter than aluminum (2.7 g/cm^3) and over four times lighter than steel (7.86 g/cm^3). Commercial cast magnesium alloys for automotive applications are AZ and AM series alloys. Fuel saving advantages of magnesium used in vehicles gives it a greater popularity. The data indicate that the overall weight savings could be of around 10%. Magnesium has very good machining abilities like punching, drilling, milling, turning compared to other metals[1]. Magnesium and aluminum alloys have become the key materials in accomplishing a new era of lighter, more efficient vehicles. Magnesium is more lighter than aluminum and its provides the best solution for fuel cells, structures and internal combustion engines. In recent times magnesium improves fuel economy by reducing power train mass in replacing aluminum[2].

Milling is one of the most extensively used metal removal processes in industry and milled surfaces are largely used to mate with other parts in die, automotive, aerospace and machinery design as well as in manufacturing industries[3]. End milling process is one of the most common metal cutting operations used for machining parts because of its ability to remove materials faster with a reasonably good surface quality[4]. End milling operation is connected with surface roughness due to some necessities such as machining efficiency, high-quality surfaces, dimensional accuracy and the process reliability[5].

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Surface roughness is an important assess of product quality since it greatly influences the performance of mechanical parts as well as production cost. Surface quality (roughness) has an contact on the mechanical properties like fatigue behavior, corrosion resistance[6]. Surface roughness is a result of many factors including tool geometry, cutting parameters, work piece material, chatter and cutting fluids[7]. Surface roughness is defined as the deviations of any material resulting from machining operations. It is denoted by R_a – namely, average roughness. R_a is theoretically derived as the arithmetic average value of departure of the profile from the mean line along a sampling length[8]. In recent times, Computer Numerically Controlled (CNC) machine tools have been implemented to utilize full automation in milling since they provide greater improvements in productivity and increase the quality of the machined parts and require less worker input. CNC milling is one of the most popular and efficient machining operations[9]. It is hard to achieve good surface quality without the proper selection and control of the process parameters[10]. So, Ghani et al. considered Taguchi method for optimization of surface roughness in end milling of hardened steel in terms of cutting parameters[11]. Zhang et al. presented a study of the Taguchi design function to optimize surface quality in a CNC face milling operation. This study included spindle speed, feed rate and depth of cut as control factors[12]. Bagci and Aykut were used the Taguchi optimization technique for small surface roughness value (R_a) in terms of cutting parameters (Spindle speed, feed rate and depth of cut) in CNC face milling of Cobalt based alloy[13]. Routara et al. investigated the influence of machining parameters (spindle speed, depth of cut and feed rate) on the quality of surface produced in CNC end milling[14]. The RSM is an active and primary important tool of Design of Experiment (DOE) where in the relationship between process output(s) and its input decision variables, it is mapped to achieve the objective of maximization or minimization of the output properties. RSM was successfully applied for prediction and optimization of cutting parameters[15]. Mansour and Abdalla have developed a surface roughness model for end milling of EN32M by employing cutting parameters of speed, feed, and depth of cut[16]. Fuht et al. studied the control of tool geometries (nose radius and flank width) and machining parameters (cutting speed, feed rate and depth of cut) on surface roughness in end milling of Al alloy by using RSM[17]. Oktem et al. analyzed the optimum cutting condition leading to a minimum roughness (R_a) in end milling by combining RSM with neural network and genetic algorithm for Al and plastic mold parts[18]. Alauddin et al. developed the mathematical model of surface roughness for the end milling of 190 BHN steel considering only the Centre Line Average (CLA) roughness parameter (R_a) in terms of cutting speed, depth of cut and feed rate using Response Surface Method (RSM)[19]. Reddy et al. developed a mathematical model for surface roughness considering the cutting parameters and tool geometry during end milling of medium carbon steel using RSM[20]. Wang et al. investigated the influence of micro-end-milling cutting conditions on roughness of a brass surface using RSM[21].

From the above literature reviews, surface roughness optimization in the end milling operation shows that spindle speed, feed rate and depth of cut have been commonly chosen as the control factors. The average surface roughness (R_a) has been the most common parameter to define the surface roughness of the machined part. In the present work, effect of machining parameters on surface roughness was investigated using RSM. Optimum machining parameters were carried out using RSM with Box-Behnken design and compared to the experimental results.

2. Experimental Details

2.1 Design of Experiments

The design of experiments technique is an important tool, which permits us to carry out the modeling and analysis of the control of process variables on the response variables. The response variable is an unknown function of the process variables, which are known as design factors. There are a large number of parameters that can be considered for machining of a particular material in end milling[4]. In the present study, 15 numbers of experiments based on a three level – three factors Box-Behnken design in RSM were performed to obtain surface roughness values calculated from magnesium AM60 alloy under dry conditions. The machining parameters such as spindle speed, depth of cut and feed rate are considered as design factors. The process variables and there levels as shown in Table 1.

2.2 Experimental Factors, Workpiece Material and Cutting Tools used

The machine used for the milling experiment is a FANUC O-IMC series three axis CNC Vertical Machining Centre (VMC) with 7.5 kW driver motor. CNC part programs were used for to describe the tool path. A magnesium

AM60 alloy block of 240 x 120 x 60 was used in the present study. The chemical compositions of magnesium AM60 alloy as shown in Table 2. The experiment was carried out with TiN coated carbide end mill cutter with 10 mm diameter and four flutes. End milling of material in the CNC machine as shown in Figure 1. The workpiece material is mounted onto the CNC machine table to provide maximum rigidity. The workpiece material is parallel to the machine table and perpendicular to the machine's spindle head. The experiment was carried out under dry condition.

Figure 1. End milling operations on the workpiece.

Table 1. Process parameters and levels used in the experimentation

Parameter	Code	Unit	Level – 1	Level – 2	Level – 3
Spindle speed	S	Rpm	1000	1500	2000
Feed rate	F	mm/rev	0.1	0.15	0.2
Depth of cut	D	Mm	0.5	1.0	1.5

2.3 Measurement of Surface Roughness

Surface roughness is an important measure of the technological quality of a product and a factor that greatly influences manufacturing cost. Surface roughness is defined as undying irregularities remained from various machining process. The average roughness (R_a) used commonly for its popular in industry[6]. In the present study, 15 experiments (Trail 1) were conducted and 15 R_a values were measured from the machined area. Each of 15 R_a values was repeated at least two times and then, the average of these values was recorded by a SURFTEST SJ–410 roughness instrument. These 15 experiments (Trail 2) were repeated and R_a values were measured. Average roughness values were calculated from the trail 1 and trail 2. Measured surface roughness values are shown in Table 3. Surface roughness measurements recorded in the perpendicular to cutting direction. 6 mm cutoff length was set for roughness measurement. Surface roughness measurement in the material by using SURFTEST SJ-410 roughness instrument as shown in Figure 2.

Table 2. Chemical compositions of magnesium AM60 alloy (wt. %)

Mg	Al	Mn	Fe	Zn	Si
93.44	6.12	0.42	0.006	0.01	0.002

Figure 2. The setup of surface roughness measurement.

3. Results and Discussion

The outcomes from the machining trails were input into the MINITAB 16 software for the further analysis. A quadratic polynomial regression model was formed by employing the roughness values to illustrate the fitness of experimental measurements. The results obtained from multiple regression analysis as shown in Table 4. In Table 4, R^2 value is 98.49% and adjusted R^2 value is 95.76%, which is desirable. When adjusted R^2 value close to 100%, the multiple regression models match very well with experimental measurements. Adjusted R^2 value 95.76% also agrees with the multiple regression models and provides a very good relationship between machining parameters such as spindle speed, feed rate and depth of cut and surface roughness.

The following equation was the final regression model in terms of coded factors for surface roughness:

Table 3. Experimental results for surface roughness

Run order	Spindle speed, S, (rpm)	Feed rate, F, (mm/rev)	Depth of cut, D, (mm)	Trail 1 Surface roughness (μm)	Trail 2 Surface roughness (μm)	Average surface roughness, R_a, (μm)
1	1500	0.15	1.0	0.337	0.320	0.329
2	1500	0.20	0.5	0.512	0.492	0.502
3	1500	0.10	0.5	0.307	0.305	0.306
4	1000	0.20	1.0	0.538	0.544	0.541
5	1000	0.10	1.0	0.303	0.321	0.312
6	1000	0.15	1.5	0.398	0.426	0.412
7	1500	0.15	1.0	0.356	0.338	0.347
8	2000	0.15	0.5	0.296	0.304	0.300
9	2000	0.15	1.5	0.341	0.353	0.347
10	2000	0.10	1.0	0.331	0.257	0.294
11	1500	0.10	1.5	0.335	0.317	0.326
12	2000	0.20	1.0	0.543	0.541	0.542
13	1000	0.15	0.5	0.373	0.359	0.366
14	1500	0.20	1.5	0.560	0.578	0.569
15	1500	0.15	1.0	0.329	0.321	0.325

$$
\begin{aligned}
R_a = {} & 0.964833 - 0.000181S - 7.95F \\
& - 0.131333D + 0.0000000381667S^2 \\
& + 31.6167F^2 + 0.0521667D^2 \\
& + 0.00019SF + 0.00001SD + 0.47FD
\end{aligned}
$$

Analysis of Variance (ANOVA) analysis was carried out to determine the effect of machining parameters on the surface roughness. An ANOVA table commonly used to summarize the tests performed. An ANOVA table for response surface quadratic model for surface roughness as shown in Table 5. The P test was used to evaluate the statistical significance of machining parameters for surface roughness. The P value for these machining parameters is less than 0.05 (i.e. 95% confidence level). This demonstrates that machining parameters have a significant effect on the surface roughness. Table 5 shows the contribution of each parameter on the surface roughness. Spindle speed, feedrate and depth of cut affect the surface roughness by 1.99%, 76.18% and 2.94% respectively. The normal probability plot of the residuals for the surface roughness as shown in Figure 3. This illustrate that residuals generally fall on the straight line showing that the errors are distributed normally. The plot of the residuals versus fitted value for surface roughness as shown in Figure 4. This revealed that they have no obvious pattern and unusual structure. This shows that model proposed was adequate.

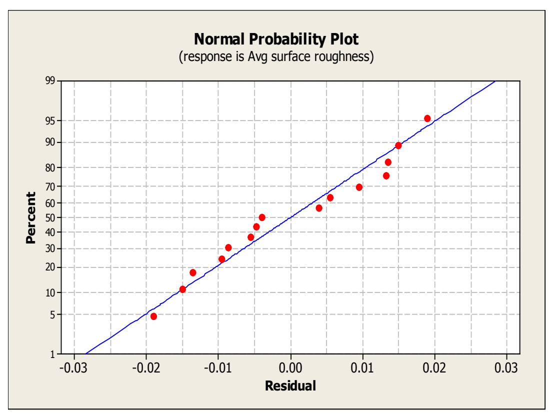

Figure 3. Normal probability plot of residuals for R_a.

The response surface contour plots for influence of machining parameters (Speed, feed and depth of cut) on the surface roughness were shown in Figures 5 and 6. It is clear from Figure 5 that at any particular depth of cut, the better surface roughness is obtainable when speed is higher at the spindle speed range experimented and feed is lower at the feed rate range experimented. Figure 6 shows that at any particular speed, the surface roughness increases with increasing feed rate and depth of cut so, the

Table 4. Estimated regression coefficients for average surface roughness

Term	Coef	SE Coef	T	P
Constant	0.333667	0.011787	28.307	0.000
Speed	-0.018500	0.007218	-2.563	0.050
Feed	0.114500	0.007218	15.862	0.000
Depth	0.022500	0.007218	3.117	0.026
Speed*Speed	0.009542	0.010625	0.898	0.410
Feed*Feed	0.079042	0.010625	7.439	0.001
Depth*Depth	0.013042	0.010625	1.227	0.274
Speed*Feed	0.004750	0.010208	0.465	0.661
Speed*Depth	0.000250	0.010208	0.024	0.981
Feed*Depth	0.011750	0.010208	1.151	0.302
S = 0.0204165 PRESS = 0.02957				
R-Sq = 98.49% R-Sq(pred) = 78.52% R-Sq(adj) = 95.76%				

Table 5. Analysis of Variance for average surface roughness

Source	DF	Seq SS	Adj SS	AdjMS	F	P	Contribution (%)
Regression	9	0.135594	0.135594	0.015066	36.14	0.001	
Linear	3	0.111670	0.111670	0.037223	89.30	0.000	
Speed	1	0.002738	0.002738	0.002738	6.57	0.050	1.99
Feed	1	0.104882	0.104882	0.104882	251.62	0.000	76.18
Depth	1	0.004050	0.004050	0.004050	9.72	0.026	2.94
Square	3	0.023281	0.023281	0.007760	18.62	0.004	
Speed*Speed	1	0.000033	0.000336	0.000336	0.81	0.410	0.02
Feed*Feed	1	0.022620	0.023068	0.023068	55.34	0.001	16.43
Depth*Depth	1	0.000628	0.000628	0.000628	1.51	0.274	0.46
Interaction	3	0.000643	0.000643	0.000214	0.51	0.690	
Speed*Feed	1	0.000090	0.000090	0.000090	0.22	0.661	0.07
Speed*Depth	1	0.000000	0.000000	0.000000	0.00	0.981	0.00
Feed*Depth	1	0.000552	0.000552	0.000552	1.32	0.302	0.40
Residual Error	5	0.002084	0.002084	0.000417			
Lack-of-Fit	3	0.001810	0.001810	0.000603	4.39	0.191	1.31
Pure Error	2	0.000275	0.000275	0.000137			0.20
Total	14	0.137678					100

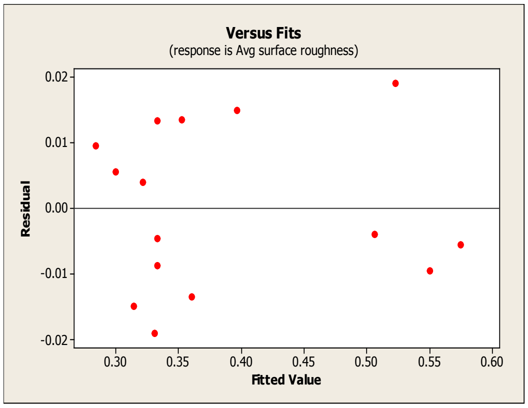

Figure 4. Plot of residual vs. fitted value for R_a.

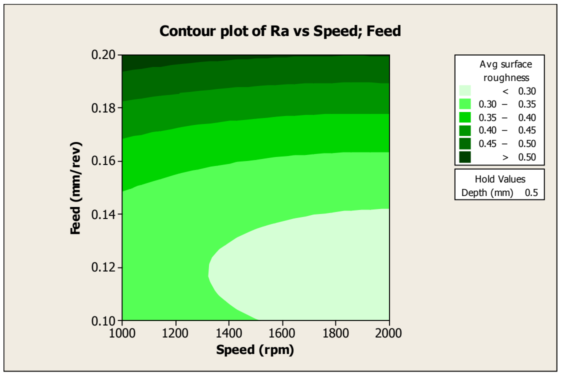

Figure 5. R_a contours in speed-feed plane at depth of cut of 0.5 mm.

lower feed rate and depth of cut implies minimum surface roughness. Spindle speed 2000 rpm, feed rate 0.1 mm/rev and depth of cut 1.0 mm were the optimal parameters for the low surface roughness in magnesium AM60 alloy.

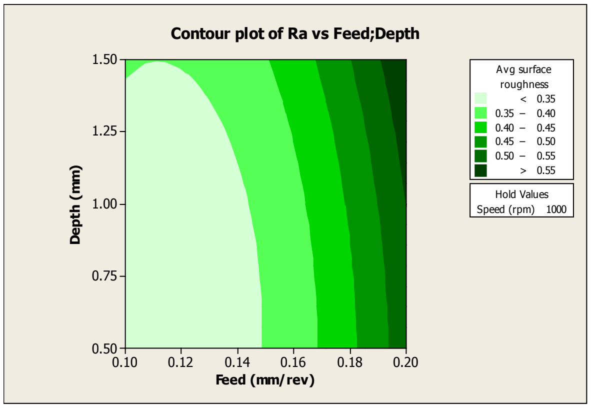

Figure 6. R_a contours in feed-depth plane at speed of 1000 rpm.

4. Confirmation Experiment

A confirmation experiment was an important process for to validate the predicted optimal values after experimental trails. In the present work confirmation experiment was conducted for the optimal machining parameters such as spindle speed 2000 rpm, feed rate 0.10 mm/rev and depth of cut 1.0 mm. The surface roughness (R_a) value was repeated at least two times and then, the average surface roughness value was measured by SURFTEST SJ-410 instrument. The measured surface roughness value (0.297) was very close to the minimum surface roughness (0.294) in the Table 3. Thus, the confirmation experiment revealed that the selection of the optimal levels for all the machining parameters produced low surface roughness.

5. Conclusions

In the present learn, the better combinations of machining parameters have been selected to supply the lower surface roughness in the milling of the magnesium AM60 alloy under dry condition. Quadratic polynomial regression model was developed based on RSM using Box-Behnken design. The developed RSM model was tested through ANOVA. An ANOVA analysis was performed to indicate the influence of three machining parameters on the surface roughness. The following conclusions were summarized from the above investigations:

- From the regression analysis, R^2 was found to be 98.49% and adjusted R^2 was 95.76%. Therefore, the surface roughness (R_a) values are adequate to construct the prediction model for surface roughness.
- From ANOVA results, the feed rate was found to be most significant factor affects surface roughness of milled surface. Depth of cut and spindle speed were other machining parameters affecting the surface roughness. Feed rate, depth of cut and spindle speed affects the surface roughness by 76.18%, 2.94% and 1.99% respectively.
- Contour plots clearly show the surface roughness increases rapidly with the increases in feed rate and depth of cut. So, it is recommended to employ smaller feed rate and depth of cut to achieve low surface roughness.
- It can be concluded that RSM method is effective and efficient method to optimize milling parameters for low surface roughness.

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