

Influence of Cutting Parameters in Face Milling Semi-Solid AA 2024 Using a Carbide Tool Affecting the Surface Roughness and Tool Wear

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Abstract

The aim of this research was to investigate the effects of the main factors on the surface roughness in aluminum semi-solid 2024 face milling. This study was conducted using a computer numerical controlled milling machine having 63 mm diameter fine type carbide tool with a twin cutting edge. The variable factors investigated were speed, feed rate and depth of cut being not over 1 mm. For this experiment, the factorial designs were applied. The results revealed that the factors that significantly affect the surface roughness were the speed and feed rate; while the depth of cut did not affect the result. An increase in the speed and a decrease in the feed rate tended to reduce the surface roughness. Besides, the results obtained from this research could be employed to generate the linear equation of $R_a = 0.205 - 0.000022 \text{ Speed} + 0.000031 \text{ Feed rate}$. Lastly, the flank and crater wears were observed at a tool life of 1,450 min.

Keywords: CNC milling machine, semi-solid AA 2024, surface roughness, tool wear

Introduction

Aluminum alloys are extensively used as main engineering materials in various industries such as automotive industries, mold and die component manufactures and the industries in which weight is the most important factor. Surface roughness is an important measurement for product quality since it greatly affects the performance of mechanical parts as well as production cost. These materials help machining and possess superior machinability index. Milling is one of the most commonly used machining processes in aluminum alloys shaping. It is of considerable economic importance because it is usually among the finishing steps in the fabrication of industrial parts. Their effects on products are so important because they may cause some critical problems such as the deterioration of surface quality that may reduce the product durability and precision.

As mentioned above, the surface roughness is an important measurement for product quality. It has an impact on the mechanical properties such as fatigue behavior, corrosion resistance, creeps life, etc. Sometimes, various catastrophic failures causing high cost attributes to the surface finish of the components in question. As a result, there have been many great research developments in the modeling of surface roughness and the optimizing of controlling parameters to obtain a surface finish of a desired level since only proper selection of cutting parameters can produce a better surface finish. Nevertheless, such studies are far from complete since it is very difficult to consider all of the parameters that control the surface roughness of a particular manufacturing process. The parameters that affect the surface

roughness include machining parameters, cutting tool properties and workplace properties. In the manufacturing industries, various machining processes are adopted to remove the material from a workpiece for better products. Similarly, the end milling process is one of the most vital and common metal cutting operations used for machining parts because of its ability to remove materials faster with a reasonably good surface quality. In recent years, numerical controlled machine tools have been implemented to realize full automation in milling because they provide a greater improvement in productivity, increase the quality of the machined parts, and require less operator input.

A brief review of the literature related to roughness modeling in milling is presented herein. Alauddin *et al.* [1] developed a mathematical model of surface roughness for the end milling of 190 BHN steel considering only the center line average roughness parameter in terms of cutting speed, feed rate and depth of cut using the response surface method. After that, the effects of spindle speed, feed rate and depth of cut were studied on the roughness in end milling of aluminum workpiece. They used the in-process surface roughness recognition and neural fuzzy system to predict the roughness [2,3]. Later, Dweiri *et al.* [4] considered the Neuro-fuzzy approach for roughness modeling in CNC down milling of Al₆₀₆₁-T6; while Ghani *et al.* [5] considered the Taguchi method for optimizing the surface roughness in end milling of hardened steel in terms of cutting parameters. Subsequently, Brezocnik *et al.* [6] used genetic programming for surface roughness prediction in CNC end milling of 6061 Al in terms of machining parameters as well as vibrations. In the same year, Wang and Chang [7] investigated the surface roughness in slot end milling of aluminum and analyzed the optimum cutting conditions leading to a minimum surface roughness in end milling by combining the response surface method with neural networks and genetic algorithms for aluminum and plastic mold parts [8,9]. Afterwards, Wang *et al.* [10] investigated the influence of micro-end-milling cutting conditions on the surface roughness of a brass surface using a response surface method. Reddy and Rao [11] developed a mathematical model for surface roughness considering cutting parameters and tool geometry during end milling of medium carbon steel using the response surface method. After that, Ozcelik and Bayramoglu [12] modeled the surface roughness in high speed flat end milling of steel, including total tool operating time along with other machining variables such as spindle speed, feed rate, depth of cut and step over. Later, Ryu *et al.* [13] incorporated the effects of a cutting edge angle on roughness and a texture generation on end milled steel surfaces. They have used the response surface method deviation, skewness and kurtosis for evaluating the generated surface texture characteristics. Recently, Bagci and Aykut [14] used the Taguchi optimization method for low surface roughness values in terms of cutting parameters in the CNC face milling of a cobalt based alloy. More recently, Chang and Lu [15] presented the optimization of cutting parameters for side milling of medium carbon steel with multiple roughness characteristics, viz., feeding direction roughness, axial direction roughness and waviness, using a gray relational Taguchi approach.

Cutting aluminum alloys is a major manufacturing process in the automotive industry and the manufacturing of mold and die components. Milling with an end mill is one of the important machining processes for making profiles, slots, engraving, surface contouring, and pockets in precision molds and dies. The machining process is used in both roughing and finishing operations. Thus, the forming process, including planning machining, milling, and surface milling create a loss of material. The problems probably are caused by several factors such as material, cutting speed, feed rate, cutting depth, and also workers having no experience. Therefore, the researcher was interested in investigating optimal conditions in aluminum semi-solid 2024 milling processes to benefit the automotive industry and the manufacturing of mold and the die components industries in order to reduce times and cost to obtain the best quality product.

Equipment and tools

This current work aimed at investigating the effects of the main factors on the surface roughness in aluminum semi-solid 2024 face milling process. The following equipment and instruments were used: a computer numerical controlled (CNC) milling machine model DMG type DMC 835N having the technical specifications of maximum speed of 18,000 rpm and maximum feed rate of 20,000 mm/min. A face milling chuck employed the fine type carbide tool with a 63 mm diameter edge and twin cutter type

of a maximum speed of 18,000 rpm using the carbide cutting tool model of Kennametal type KEGT25L512PEERLDJ. In addition, the surface roughness was measured by the surface roughness tester model Mitutoyo Surf Test SJ-201. The wear of the cutting tool was observed by using a scanning electron microscope (SEM; FEI Quanta 400).

Casting method for aluminum semi-solid 2024

The 2024 aluminum alloy was melted in a graphite crucible using an electrical resistance furnace at 750 °C. Approximately 500 g of molten aluminum was taken from the crucible in the furnace using a ladle cup. Then, the aluminum semi-solid 2024 was prepared using the gas induced semi-solid (GISS) technique. A gas bubble was introduced to the molten alloy at a temperature of 643 °C for 10 s; and, the molten aluminum was then held for 15 s before squeeze casting. The slurry was poured into a die cavity. The applied pressure of 66 MPa was achieved from a 100 tons hydraulic press. The upper die and lower die were preheated to 350 °C [16]. Chemical composition of aluminum semi-solid 2024 is shown in **Table 1**. **Figure 1** shows the microstructure of the casting aluminum semi-solid 2024 before the machining operation was performed.

Table 1 Chemical composition of aluminum semi-solid 2024.

Element	Al	Si	Fe	Cu	Mn	Mg	Zn	Ti
Weight (%)	93.78	0.34	0.19	3.50	0.61	1.29	0.28	0.01

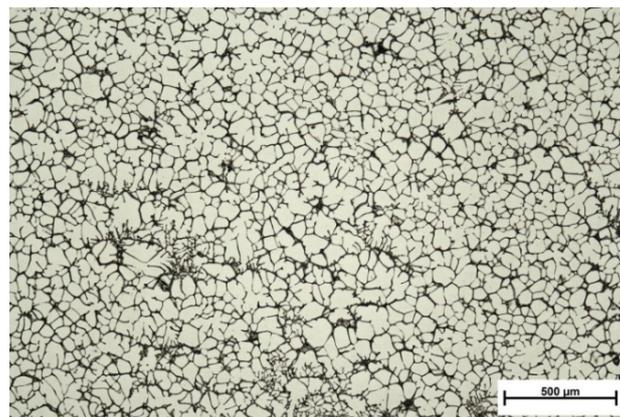


Figure 1 Microstructure of aluminum semi-solid 2024.

Methodology

There were 4 main procedures that were conducted to achieve the purposes of this study. Firstly, we investigated the sample size for designing the face milling. Secondly, we studied the expected factors affecting the surface roughness in the semi-solid 2024 milling process. Thirdly, we examined the optimal conditions in the semi-solid 2024 milling on surface roughness; and, finally the optimal conditions were conducted in milling to compare the results between the actual and predicted values. These were detailed as follows:

Procedure no. 1: we investigated the sample size to design the experiment for the aluminum semi-solid 2024 milling by using Minitab R.16 software with statistical reliability and significance at 95 % and 5 %, respectively.

Procedure no. 2: we studied the factors affecting the surface roughness in the aluminum semi-solid 2024 face milling process by using completely randomized factorial designs with 5 repeated treatments for reducing the variation of sampling. The Minitab R.16 software was employed to design the 2³ factorial and to analyze the statistical values [17-19]. The 3 main factors and the upper and lower limits of experimental ranges for each factor are shown in **Table 2**.

Table 2 Selected factors and their constraints for the 2³ factorial design of experiments.

Factors	High	Low
Speed (rpm)	3,400	2,400
Feed rate (mm/min)	1,400	1,000
Depth of cut (mm)	1	0.5

Procedure no. 3: a general factorial design was used for identifying the optimal surface roughness (R_a) with the allocated speed of 3 levels: 2400, 3000 and 3600 rpm; and, the allocated feed rate was classified into 3 levels; 1000, 1200 and 1500 mm/min. Furthermore, the depth of cut was fixed at 0.5 mm due to its lack of influence on the surface roughness, which was the experimental result from procedure no. 2. The factors considered in the experiment are shown in **Table 3**.

Table 3 Factors and their constraints for the 3³ factorial design of experiments.

Factors	Level 1	Level 2	Level 3
Speed (rpm)	3,600	3,000	2,400
Feed rate (mm/min)	1,500	1,200	1,000
Depth of cut (mm)	0.5	0.5	0.5

Procedure no. 4: we machined the conditions obtained from the prediction of a linear equation from procedure no. 3 to compare the surface roughness between the actual and predicted values. The confirmation was conducted by randomly selecting 12 cutting conditions as well as replicating each condition 3 times.

Results and discussion

The experiment for finding the sample sizes used surface roughness values in statistical analysis with a confidence of 95 % or significance of 5 %. The feed rate at 1,600 mm/min, the speed at 2,600 rpm and the depth of cut at 1 mm were employed in the milling experiment. The 12 repeated treatments revealed that the average surface roughness was 0.20 μm with a standard deviation of 0.018 μm . From the statistical analysis with software, it was found that the appropriate size was 5 samples with 95 %, reliability.

According to procedure no. 2, the analysis of the variance for the surface roughness was shown in **Table 4**. The coefficient of determination (R^2) and the adjusted coefficient of determination ($\text{adj-}R^2$) were 80.10 and 75.75 %, respectively. This result implies that if the variance value was 100 μm^2 , the 80.10 μm^2 could be explained with a regression model; and, the 19.9 μm^2 was not explainable due to uncontrollable variables in the experiment. The R^2 values of about 100 indicate the experiment is satisfactory [18]. From these results, it can be concluded that this experiment is appropriate and accurate.

Table 4 reveals that the main factors that significantly (P -value < 0.05) affect the surface roughness of aluminum semi-solid 2024 are the speed and the feed rate. In **Table 5**, an increase in speed from 2,400 to 3,400 rpm reduced the surface roughness. Likewise, it was also found that the surface roughness increased with an increase in the feed rate from 1,000 to 1,400 mm/min. In the case of the depth of cut, it was found that it did not affect the surface roughness. Furthermore, in **Table 4** it also showed that the interaction effects between the factors insignificantly (P -value > 0.05) affected the surface roughness of aluminum semi-solid 2024.

Table 4 Analysis of variance on surface roughness values.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Speed	1	0.0067860	0.0067860	0.0067860	82.29	0.000*
Feed rate	1	0.0027390	0.0027390	0.0027390	33.22	0.000*
Depth of cut	1	0.0002162	0.0002162	0.0002162	2.62	0.115
Speed*Feed rate	1	0.0002862	0.0002862	0.0002862	3.47	0.072
Speed*Depth of cut	1	0.0001122	0.0001122	0.0001122	1.36	0.252
Feed rate*Depth of cut	1	0.0002862	0.0002862	0.0002862	3.47	0.072
Speed*Feed rate*Depth of cut	1	0.0001980	0.0001980	0.0001980	2.40	0.131
Error	32	0.0026388	0.0026388	0.0026388		
Total	39	0.0132628				

S = 0.00908089, R² = 80.10 %, Adjusted R² = 75.75 %

* P -value less than 0.05 is considered significant.

Table 5 Effect of factors for the 2³ factorial design on surface roughness values.

Speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	R _a (μm)
2,400	1,000	1.0	0.230
3,400	1,000	1.0	0.191
2,400	1,000	0.5	0.212
2,400	1,400	0.5	0.233
3,400	1,400	0.5	0.211
3,400	1,400	1.0	0.212

Based on procedure no. 3, the data analysis was conducted to identify the variation of surface roughness for semi-solid AA2024. The values of R² and adj-R² for the surface roughness in **Table 6** are 81.19 and 78.40 %, respectively. This result means that if the variance value was 100 μm², the 81.19 μm² could be explained by the regression model, and the 18.81 μm² was not explainable due to the uncontrollable variables in the experiment. Therefore, the data variance in the measurement of the surface roughness could be implied from the speed and feed rate. From these results, it can be concluded that this experiment is appropriate and accurate.

Table 6 shows that the speed and feed rate significantly (P -value < 0.05) affected the surface roughness of aluminum semi-solid 2024. Likewise, in **Table 7** an increase of speed from 2,400 to 3,000 and 3,600 rpm reduced the surface roughness; whereas the surface roughness increased by increasing the feed rate from 1,000 to 1,200 and 1,500 mm/min. In addition, the interaction effects between the speed and feed rate do not affect the surface roughness of aluminum semi-solid 2024, as shown in **Table 6**. This implies that they together were independent on the surface roughness.

Table 6 Analysis of variance on surface roughness values.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Speed	2	0.0075602	0.0075602	0.0037801	83.88	0.000*
Feed rate	2	0.0026452	0.0026452	0.0013226	29.35	0.000*
Speed*Feed rate	4	0.0002971	0.0002971	0.0000743	1.65	0.176
Error	54	0.0024334	0.0024334	0.0000451		
Total	62	0.0129359				

S = 0.00671293, R² = 81.19 %, Adjusted R² = 78.40 %

*P-value less than 0.05 is considered significant.

Table 7 Effect of factors for the 3³ factorial design on surface roughness values.

Speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	R _a (μm)
2,400	1,000	0.5	0.181
3,000	1,000	0.5	0.170
3,600	1,000	0.5	0.155
2,400	1,000	0.5	0.181
2,400	1,200	0.5	0.189
2,400	1,500	0.5	0.202

The speed and feed rate factors were employed to analyze the regression model for the surface roughness of aluminum semi-solid 2024. The analysis was carried out using the data obtained from the various experiments. A total of 3 levels of speed were set: 2400, 3000 and 3600 rpm; and, the ratio of feed rate were classified into 3 levels: 1000, 1200 and 1500 mm/min. Further, the depth of cut was fixed at 0.5 mm. The regression model analysis was conducted using the Minitab R.16 software. The findings are shown in **Table 8**. The analysis of the regression model generated a linear equation that provides the relationship between the main factors and the surface roughness (R_a), as shown in Eq. (1).

$$R_a = 0.205 - 0.000022 \text{ Speed} + 0.000031 \text{ Feed rate} \quad (1)$$

The result from procedure no. 4 confirmed all of the treatments studied by using an algebraic equation to predict the surface roughness of aluminum semi-solid 2024. The sampling of cutting process within the limited area can be compared to the actual means. The error between the actual and predicted values has goals less than 5 %. From the experimental results as shown in **Figure 2**, the mean absolute percent error (MAPE) as calculated in Eq. (2) was 3.48 %. Thus, the difference between the actual and predicted values is acceptable.

$$\text{MAPE} = \frac{1}{n} \left(\sum_{t=j}^T \frac{|e_t|}{d_t} \times 100 \right) \quad (2)$$

Table 8 Regression analysis: Surface roughness values, speed and feed rate.

Regression analysis: Ra versus speed, feed rate				
The regression equation is $Ra = 0.205 - 0.000022 \text{ Speed} + 0.000031 \text{ Feed rate}$				
Predictor	Coef.	SE Coef.	T	P
Constant	0.205363	0.007443	27.59	0.000
Speed	-0.00002234	0.00000176	-12.70	0.000
Feed rate	0.00003114	0.00000420	7.42	0.000
S = 0.00684300, R ² = 78.3 %, Adjusted R ² = 77.6 %				

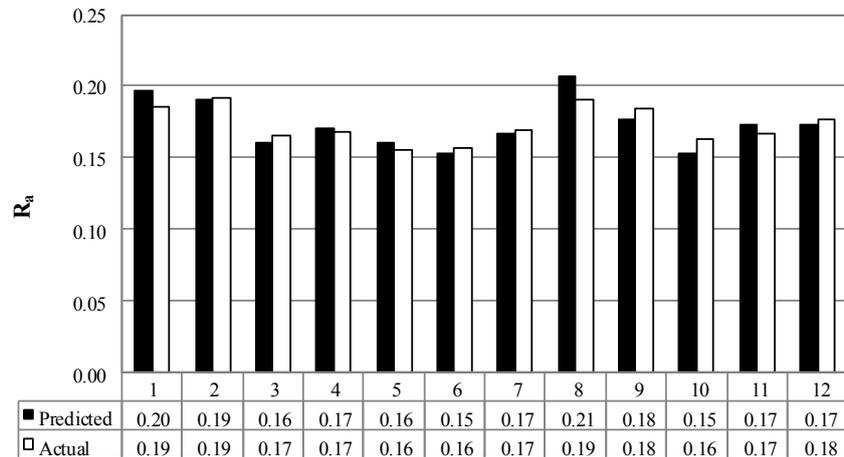


Figure 2 Comparison of the surface roughness between actual and predicted values.

In addition, the wear of the cutting tool were also observed by using the SEM. **Figures 3(a)** and **3(b)** displayed the wear mechanism on the flank and crater faces, respectively, when machining at a cutting speed of 3,600 rpm, feed rate of 1,300 mm/min and depth of cut of 1 mm. At these cutting conditions the longest tool life of 1,450 min was obtained. The investigation under the SEM exhibited that the wear on the flank and crater faces were uniform. This phenomenon occurred due to the stress concentration which led to cohesive failure [20,21]. Likewise, the flank and crater wear lands gradually increased with an increase in the cutting speed and feed rate due to higher cutting temperature that resulted in the rate of plastic deformation thereby reducing the strength of tools [22].

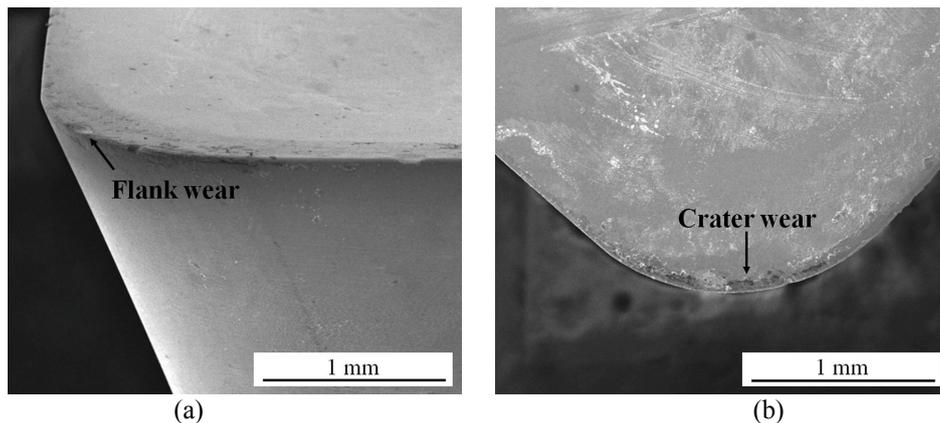


Figure 3 Wear on (a) flank face and (b) crater face.

Conclusions

The purpose of this research was to investigate the effects of main factors including speed, feed rate and depth of cut on the surface roughness in aluminum semi-solid 2024 as well as optimize the milling conditions. The completely randomized block factorial design was applied in the research. From the experiment and analyses, it may be concluded as follows;

1) The surface roughness of aluminum semi-solid 2024 was significantly affected by the cutting speed and feed rate. The results also indicated that an increase of speed and a decrease of feed rate tended to reduce the surface roughness.

2) A linear equation for optimizing the surface roughness in milling of aluminum semi-solid 2024 was: $R_a = 0.205 - 0.000022 \text{ Speed} + 0.000031 \text{ Feed rate}$

This equation could be applied with a face mill cutting tool having 2 edges with the cutting speed at 2,400 - 3,600 rpm and the feed rate at 1,000 - 1,500 mm/min.

3) The comparison of the results between the actual and predicted values in milling found that the MAPE was 3.48 %, which was fewer than the goal of 5 %. Thus, the difference between actual and predicted values is acceptable.

4) The wear of the cutting tool was observed at a tool life of 1,450 min with the conditions of speed 3,600 rpm, feed rate 1,300 mm/min and a depth of cut of 1 mm.

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