SNRU Journal of Science and Technology

Journal home page: snrujst.snru.ac.th

Application of response surface methodology for optimization of cutting parameters for surface roughness and tool wear in turning of aluminum casting semi-solid 7075

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Received: 2 January 2020; **Revised:** 5 April 2020; **Accepted:** 7 April 2020; **Available online:** 1 May 2020

Abstract

The objectives of this research were to determine the optimal cutting parameters and to predict the surface roughness and tool wear in turning process for aluminum casting semi-solid 7075 using the response surface methodology based on the Box-Behnken design. The cutting parameters investigated in this study included cutting speed, feed rate, and depth of cut. From the experiment, it was found that the main factors resulting in surface roughness were cutting speed, feed rate, and depth of cut. The optimal cutting conditions that provided for the surface roughness of 0.34 µm. were the cutting speed of 220 m. min^{-1}, feed rate of 0.02 mm. rev^{-1}, and depth of cut of 0.45 mm. Furthermore, the wear mechanism was taken place by cutting speed, feed rate and depth of cut. The pattern of wear was similar to cracking of mechanical fatigue, such as notch wear and crater wear.

Keywords: CNC turning machine; Aluminum casting semi-solid; Surface roughness; Response surface methodology

1. Introduction

Nowadays, production systems have been increasingly developed because of an expansion in manufacturing. In particular, the part production industry in Thailand has demanded higher quality and lower production cost to produce parts or products. Auto parts and plastic mould industries are also the most active sectors concerning production system development for two reasons. Firstly, it is worth noting that the system has been widely employed due to its properties regarding erosion and high temperature resistances, capability of machining, and appropriate mechanical properties. Secondly, it can be adapted for employing the system to other industries.

The industry using part transforming process by means of metal cutting require a very high accuracy technology, so that the machinery automation technology is employed to meet the standards under the same quality production. It should be noted that the metal cutting using turning is one of the most important basic-production processes. It has been employed in the forming and manufacturing processes by using the CNC Turning. In this case, it is required to choose the optimal conditions concerning metal cutting in order to prolong the lifetime of cutting metal machines and reduces the cost of the production process. Therefore, it is essential to define metal cutting parameters, so that a metal cutting machine is worth for manufacturing process. In addition, it yields maximum output and produces work with proper surface.

In case of metal cutting using turning, it was found that the prediction of surface roughness in turning using Box-Behnken Design required several factors. These included feed rate, cutting speed, depth of cut, and nose radius. It was also found that the feed rate and nose radius had more effect on the surface roughness than the cutting speed and depth of cut. Furthermore, the surface roughness was gradually decreased when the feed rate and depth of cut became lower, while the nose radius and cutting speed were higher [1]. There was also a study concerning the effects of turning factors to the surface roughness of aluminum casting semi-solid 7075 using the factorial experimental design. In this work, the factors studied included cutting speed, feed rate, and depth of cut. The results showed that the feed rate had the most influence on the surface roughness. In addition, the level of surface roughness was progressively decreased by the gradual decreasing of the feed rate [2]. After that, has analyze the surface roughness, cutting tool forces and tool wear in machining casted gray iron [3]. And some studied the optimization of surface roughness and tool wear in hard turning of austempered ductile iron [4].

Later on, there was a study concerning the factors affecting the surface roughness and wear of cutting inserts during the turning process of aluminum casting semi-solid 356 using the Harrison M 300R. The factors included cutting speed, feed rate, and depth of cut. The results showed that the most influence factor on the surface roughness was the cutting speed. Meanwhile, when the feed rate and depth of cut were progressively lower, the surface roughness was gradually decreased [5]. In addition, there were studies concerning the optimal conditions and predictions for the surface roughness as well as the hardness in the turning process of aluminum casting semi-solid 6061. The results showed that the optimal conditions for the surface roughness of 1.01 µm. and the hardness of 78.54 Hv were 113 m min^{-1} cutting speed, 0.05 mm. rev^{-1} feed rate, and 0.31 mm. depth of cut [6].

Aluminum has been utilized as aluminum alloy for the production of industrial parts because of its properties that were low density, light weight, and rusty and corrosion resistance. Though, aluminum casting semi-solid 7075 had aluminum alloy regarding Zinc and Magnesium as main components with some good properties, its welding capability was quite low, owing to its softening during welding, especially around the welding zones.

Recently, there were studies with respect to the semi-solid metal casting technology using Gas Induced Semi-Solid (GISS) technique [7 – 8]. It was achieved by spraying nitrogen gas into molten metal thereby generating the globular grain structure. This results in the denser of internal structure and the lower of air voids thereby improving the mechanical properties as well as increasing the resistance to heat. To be able to employ the GISS produced material in the production of industrial parts, it must be transformed by means of machining in order to obtain a part having the desired size and shape.

The response surface methodology was employed for evaluation of the process specific parameters in many researches. [9 – 14]. In addition, researchers also applied response surface methodology to investigate the effects of parameters on surface roughness in aluminum work pieces [1 – 6].

From the related works, there were three factors affecting the turning process: cutting speed, feed rate, and depth of cut. Hence, these parameters were studied and discussed. It should be noted that the knowledge concerning the turning operation of metal casting semi-solid using the GISS has been slightly investigated. Therefore, this research is to study the optimal conditions concerning parameters and surface roughness prediction for the turning process of aluminum casting semi-solid 7075. It aims to define factors and to choose the optimal conditions that are suitable for the turning in order to obtain a good-quality aluminum part. In addition, it aims to investigate the optimal conditions of cutting parameters for surface roughness and tool wear in turning of aluminum Casting Semi-Solid 7075 using the response surface technique with the experimental design of Box-Behnken Design.

2. Materials and methods

Tools and equipment

In this section, the tool and equipment were presented as follows: 1) The EMCO PC Turn 50 computer numerical controlled (CNC) turning machine, maximum rpm. of 2,500 rpm., and maximum feed of 750 mm. rev^{-1}, manufactured in Austria. 2) The Plansee Tizit carbine cutting tool insert type DCGT 070204FN-27 grade H10T having 6.00% of Co as cutting edge, manufactured in Germany. 3) The Mitutoyo surface roughness tester model SJ-210, manufactured in Japan.

The material employed was aluminum casting semi-solid 7075 made by the GISS technology (Gas Induced Semi-Solid) using squeezing casting, as illustrated in Fig. 1. Note that the processes for materials produced by the GISS technology with squeezing casting [7, 8] was started by first melting aluminum 7075 within a graphite crucible employing an electric resistant furnace at the temperature of 730 °C. Then, flux was applied to clean the molten aluminum. The cleaned aluminum of 500 g was moved into a furnace in order to be under the GISS to produce the aluminum casting semi-solid. During in the furnace, nitrogen gas was sprayed towards the aluminum for 10 minutes while the temperature was kept at 620 °C throughout. After that, the semi-solid aluminum was poured into a mould that was heated to 300 °C. At this stage, by using a 100 tones hydraulic machine, the pressure of 66 MPa. was applied to compress the aluminum thereby obtaining the raw samples of aluminum casting semi-solid 7075. The dimensions of the samples were 100 by 100 by 25 mm., as shown in Fig. 1(a). Then, the samples were turned to cylinders with the diameter of 25 mm. and the length of 100 mm., as shown in Fig. 1(b). Fig. 1(c) showed the microstructures of the aluminum casting semi-solid 7075 produced by the GISS technology employing squeezing casting. The chemical components of the aluminum casting semi-solid 7075 with the tensile strength of 227.50 MPa. were shown in Table 1.

(a) (b) (c)

Fig. 1 (a) and (b) Samples of aluminum casting semi-solid 7075. (c) Microstructures of aluminum casting semi-solid 7075.

Table 1 Chemical components of aluminum casting semi-solid 7075.

Elements	% Weight	Elements	% Weight
Si	0.40	Zn	5.10 – 6.10
Fe	0.50	Ti	0.20
Cu	1.20 – 2.00	Cr	0.18 – 0.28
Mn	0.30	Al	Bal.
Mg	2.10 – 2.90		
Tensile Strength (MPa) = 227.50			

Methodologies

As mentioned earlier, the purposes of this research were to determine the optimal conditions and to predict the surface roughness of aluminum casting semi-solid 7075 using a CNC. In this section, the materials and procedures were described to achieve those purposes as follows.

Design of experiment

This research concerned with the experimental design using the response surface methodology (RSM) with the Box-Behnken Design [9 – 14]. The factors studies included cutting speed, feed rate, and depth of cut. For each studied factor, there were three experimental levels: –1, 0, and +1 as shown in Table 2. The Design-Expert program version 9.1 (Stat-Ease, Inc.) was employed for the statistical analysis. It should be also noted that the surface roughness was investigated in this experiment.

Table 2 Defined factors for experiments.

Factor	Low (–1)	Medium (0)	High (+1)
Cutting Speed (m. min^{-1})	130	175	220
Feed Rate (mm. rev^{-1})	0.02	0.06	0.10
Depth of Cut (mm.)	0.45	0.65	0.85

Measurement of Surface Roughness

After a sample of aluminum casting semi-solid 7075 sample turned, it was removed to measure the surface roughness. The length of the sample turned was 75 mm. The measurement points, which was 10 mm. from the end, were divided into three parts by each angle of 120 degree. The Mitutoyo surface roughness tester model SJ-210 was employed for the task. A total of three measurements were carried out for each factor in order to obtain an average value in terms of arithmetic means. It was note that the measurement was done immediately after the turning finished in order to reduce the unexpected errors. In addition, the measurement was taken parallel to the direction of turning.

Analysis of tested results

The analysis of the results was carried out by means of reliability analysis using the ANOVA. Then, the results were further analyzed using regression and mathematical models for surface roughness. After that, the regression equations were verified and compared with the surface roughness obtained from both predicted equations and actual measured-values [15 – 17].

Tool wear

Scanning electron microscopy (SEM) equipped was used to study tool wear morphology and mechanism.

3. Results and Discussion

In the experiments, there were three independent variables: cutting speed, feed rate, and depth of cut. A total of 17 conditions were set for the turning process. The responses in terms of surface roughness from the experiments were summarized in Table 3.

Model analysis of statistical regression suitable for surface roughness

To choose the optimal model, the experimental results (Table 3.) were analyzed and the statistical regression were presented in Table 4. It was observed that the quadratic equation having Adj-R^2 of 97.72% was the most appropriate. It means that the regression model was the goodness of fit for the data [18]. Therefore, it may be concluded that the quadratic equation was suitable to predict the surface roughness of aluminum casting semi-solid 7075.

Table 3 List of experiments and roughness results for aluminum casting semi-solid 7075.

Runs	Factors			Surface Roughness (µm)			
	Cutting Speed (m. min^{-1})	Feed Rate (mm. rev^{-1})	Depth of Cut (mm)	1	2	3	Average
1	175	0.06	0.65	0.64	0.62	0.59	0.62
2	175	0.06	0.65	0.63	0.57	0.55	0.58
3	175	0.10	0.45	0.52	0.69	0.63	0.61
4	175	0.06	0.65	0.65	0.67	0.58	0.63
5	175	0.02	0.85	0.29	0.35	0.31	0.32
6	130	0.10	0.65	0.83	0.86	0.69	0.79
7	175	0.06	0.65	0.69	0.60	0.63	0.64
8	220	0.02	0.65	0.45	0.43	0.36	0.41
9	175	0.02	0.45	0.40	0.44	0.51	0.45
10	130	0.06	0.85	0.49	0.41	0.45	0.45
11	175	0.10	0.85	0.85	0.71	0.79	0.78
12	130	0.02	0.65	0.40	0.46	0.50	0.45
13	175	0.06	0.65	0.68	0.64	0.55	0.62
14	220	0.06	0.45	0.28	0.38	0.40	0.35
15	220	0.06	0.85	0.43	0.45	0.42	0.43
16	130	0.06	0.45	0.42	0.41	0.40	0.41
17	220	0.10	0.65	0.68	0.65	0.73	0.69

Table 4 Analysis and evaluation for suitable equations of the turning of aluminum casting semi-solid 7075 with respect to surface roughness by using Box-Behnken experimental design.

Summary (detailed tables shown below)					
Source	Sequential p-value	Lack of Fit p-value	Adjusted R-Squared	Predicted R-Squared	
Linear	0.0061	0.0029	0.5103	0.2544	
2FI	0.5594	0.0021	0.4773	–0.3161	
Quadratic	< 0.0001	0.5545	0.9772	0.9305	Suggested
Cubic	0.5545		0.9751		Aliased

Validation of models

The validation of models is the evaluation of their appropriateness and correctness to confirm the reliability of the models experimented. From the normal probability plot as shown in Fig. 2(a), it could be seen that there was no irregular data observed, i.e. the graph was quite linear. Thus, it may be concluded that the data was in the form of normal distribution. For the relationship between the residuals and the predicted values as shown in Fig. 2(b), it was found that the residuals were very scattered. In other words, they could not be predicted. For Fig. 2(c), it was the plot of the residuals versus the predicted values. It revealed that the data was also quite scattered, as the same as in Fig. 2(b). Thus, it may be noted that the data was stable in terms of variance and independency. The relationship between the predicted-and actual values were plotted and shown in Fig. 2(d) in order to analyze their correlation using regression models and actual experiments. It was observed that the data was quite linear. Therefore, the results confirmed that these models could be employed. In addition, it can be concluded that the models are reliable and adequate.

Regression equation and analysis of variance of surface roughness

According to the validation of the test result, they were reliable. Thus, the surface roughness was further analyzed with the variance of the factors in order to investigate which ones affected the surface roughness of aluminum casting semi-solid 7075. This was done by defining the confident and significant levels of 95% and 0.05, respectively. In addition, the Design Expert V.9.1 program was employed to obtain results as shown in Table 5. From the analysis of variance, it was found that the main factors were cutting speed, feed rate, and depth of cut, together with interactions between feed rate and depth of cut. The results revealed that these factors affected the surface roughness of aluminum casting semi-solid 7075 because the P-value was lower than the significant level of 0.05. In case of the interactions between other factors, the P-value was higher than 0.05. Therefore, it could not affect the surface roughness of aluminum casting semi-solid 7075, as can be clearly seen in Table 5. In addition, from the regression analysis, the quadratic relations between the factors could be formulated, as shown in equation (1);

$$Ra = -1.62763 + (0.013253 \times \text{Cutting Speed}) - (4.39792 \times \text{Feed Rate}) + (3.45431 \times \text{Depth of Cut}) \quad (1)$$
$$- (8.33333 \times 10^{-3} \times \text{Cutting Speed} \times \text{Feed Rate}) (1.11111 \times 10^{-3} \times \text{Cutting Speed} \times \text{Depth of Cut})$$
$$+ (9.37500 \times \text{Feed Rate} \times \text{Depth of Cut}) - (4.02469 \times 10^{-5} \times \text{Cutting Speed}^2) + (30.31250 \times \text{Feed Rate}^2)$$
$$- (3.16250 \times \text{Depth of Cut}^2)$$

From the regression equation for the surface roughness of aluminum casting semi-solid 7075, the response surface plot could be formulated, as shown in Fig. 3(a). This suggested that the surface roughness would be greater if the cutting speed was lower while the feed rate was higher. In other words, the cutting speed was greater, but the feed rate was lower.

In addition, when considering Fig. 3(b), it can be seen that if both depth of cut and feed rate were increased the surface roughness would also be increased. On the contrary, the surface roughness would decrease if both depth of cut and feed rate were decreased. Furthermore, Fig. 3(c) showed that the surface roughness would increase if the cutting speed was decreased while the depth of cut was increased. However, if the cutting speed was increased while the depth of cut was decreased, the surface roughness would be lower.

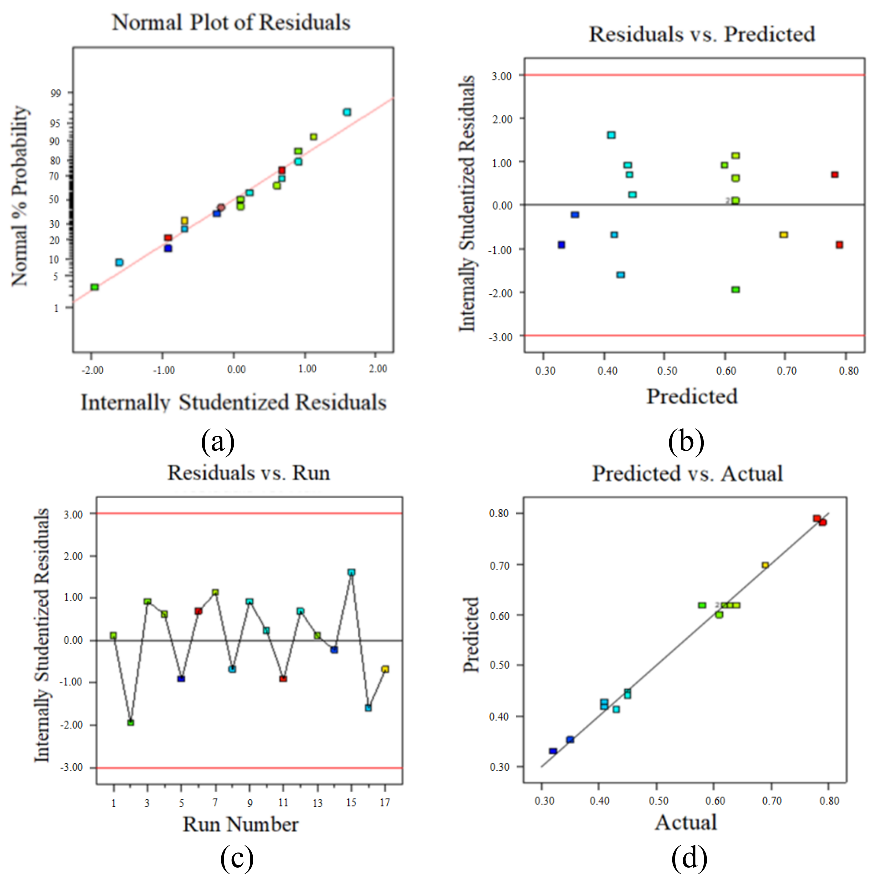


Fig. 2 Adequate evaluation of regression models concerning surface roughness (a) normal probability plot (b) residuals versus predicted values plot (c) residuals versus run values plot and (d) values versus actual values plot.

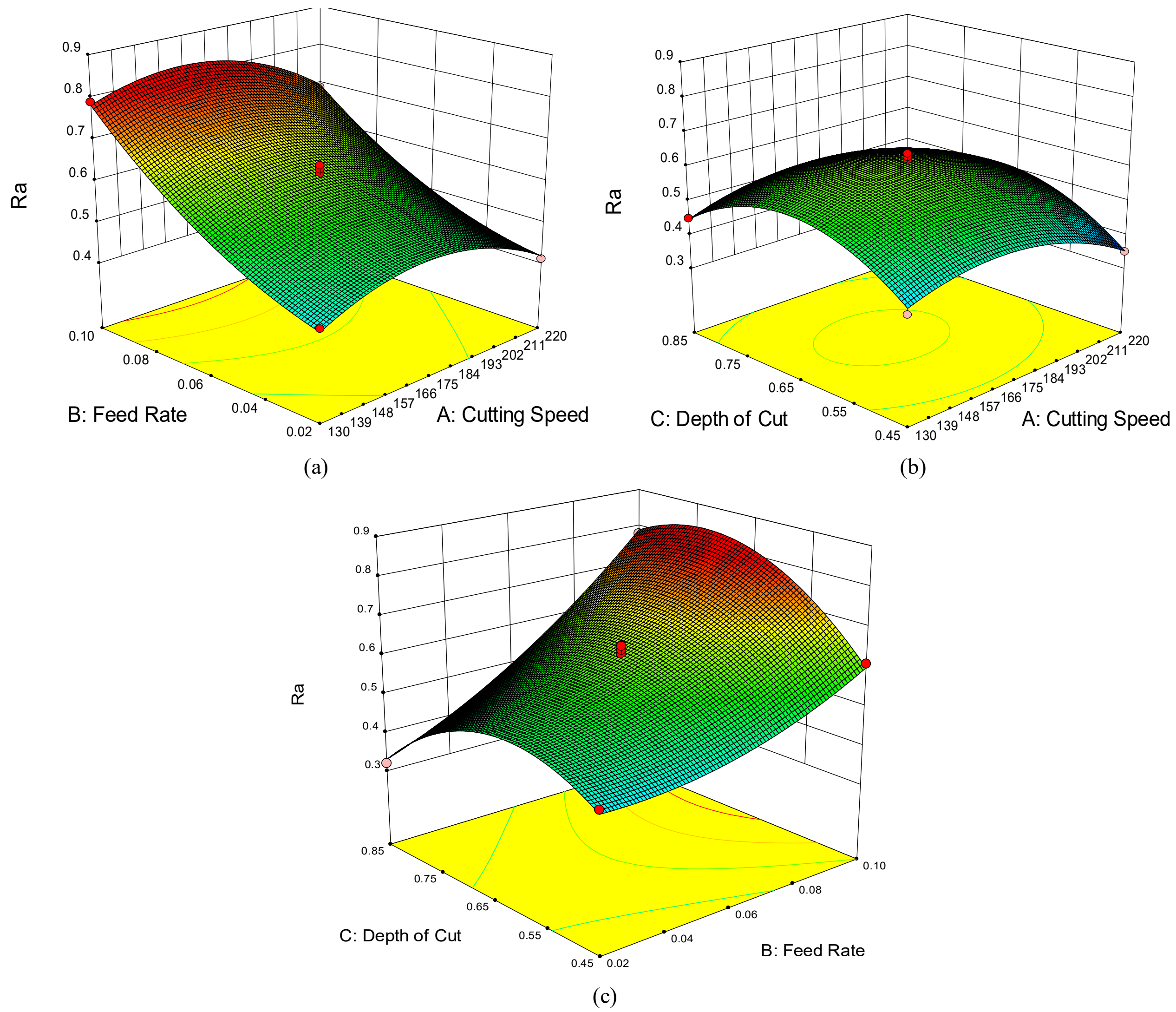


Fig. 3 (a) Effect of cutting speed and feed rate factors to surface roughness. (b) Effect of feed rate and depth of cut to surface roughness. (c) Effect of cutting speed and depth of cut to surface roughness.

Determination of the optimal conditions for surface roughness

The analysis for determining the optimal conditions based on the turning of aluminum casting semi-solid 7075 aimed to evaluate the factors resulting the minimum surface roughness. For the optimal conditions when considering the results obtained from the Design Expert V.9.1 program, were the cutting speed of 220 m. min^{-1}, the feed rate of 0.02 mm. rev^{-1}, and the depth of cut of 0.45 mm. It was noted that these optimal conditions were the surface roughness of 0.34 µm. with the desirability of 99.10%.

Experiment to confirm the surface roughness results

This step was carried out to confirm that the results obtained were in accord with the past studied [2 – 6]. It was done by using the regression equation obtained to predict the surface roughness having pre-defined turning conditions. Then, the predicted values were compared with the actual experimental data. It should be noted that deviation obtained from prediction in terms of surface roughness was set to 5% of maximum. Next, the deviation from the prediction and the experiments were analyzed. When considering the comparison of the surface roughness obtained from the prediction using the regression equation and then the experiment, it was found that overall deviation was 3.91%, which was acceptable.

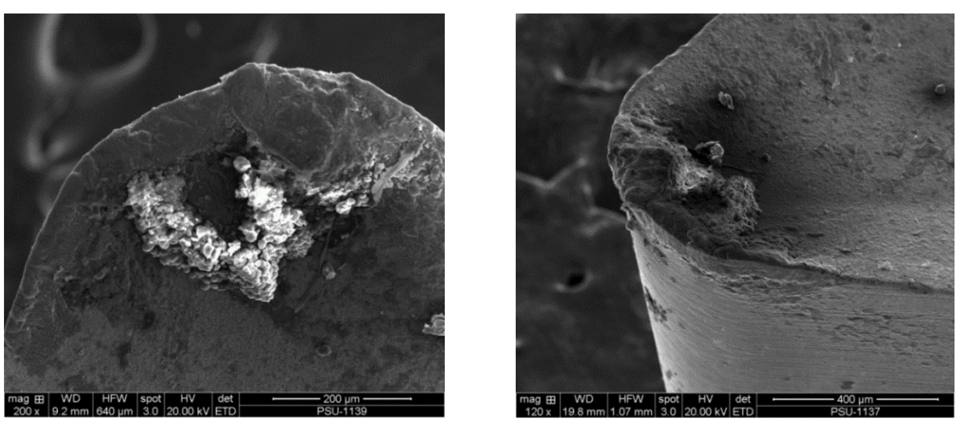
Table 5 Analysis of variance for regression models of response to surface roughness.

ANOVA for Response Surface Quadratic model					
Analysis of variance table [Partial sum of squares - Type III]					
Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**
Model	0.330	9	0.037	77.36	< 0.0001
A-Cutting Speed	6.050×10^{-3}	1	6.050×10^{-3}	12.72	0.0091*
B-Feed Rate	0.190	1	0.190	404.02	< 0.0001*
C-Depth of Cut	3.200×10^{-3}	1	3.200×10^{-3}	6.73	0.0358*
AB	9.000×10^{-4}	1	9.000×10^{-4}	1.89	0.2114
AC	4.000×10^{-4}	1	4.000×10^{-4}	0.84	0.3897
BC	0.023	1	0.023	47.30	0.0002*
A^2	0.028	1	0.028	58.79	0.0001*
B^2	9.904×10^{-3}	1	9.904×10^{-3}	20.82	0.0026*
C^2	0.067	1	0.067	141.64	< 0.0001*
Residual	3.330×10^{-3}	7	4.757×10^{-4}		
Lack of Fit	1.250×10^{-3}	3	4.167×10^{-4}	0.80	0.5545
Pure Error	2.080×10^{-3}	4	5.200×10^{-4}		
Cor Total	0.33	16			

*P-value less than 0.05 is considered significant.

Tool wear

The SEM photographs were used to analyze the wear mechanism of cutting tool with the cutting speed of 220 m. min^{-1}, the feed rate of 0.02 mm. rev^{-1}, and the depth of cut of 0.45 mm. For this cutting condition, the longest tool life was 2 hours and 25 minutes. Fig. 4(a) and (b) showed that the wear mechanism was similar to cracking of mechanical fatigue or wear mechanism on the notch and the tip of the cutting tool or a notch wear of cutting tool. In general, the fracture process and chemical reaction were mainly caused fracture at notch by excessive localized damage taking place at the notch. Moreover, the finish on the turning part and operation times had an effect on fracture wear. The high feed rate and cutting speed had an effect on the cracking and fracturing of the cutting edge, and led to catastrophic failure of the cutting edge. The fracture wear occurred in heavy tool under tough cutting conditions.



(a) (b)

Fig. 4 (a) and (b) Tool wear.

4. Conclusion

This research was concerned with the optimal of cutting parameters and prediction of surface roughness and tool wear generated from turning process using a Computer Numerical Control turning machine. It was done by employing the response surface methodology with the Box-Behnken Design. The experimental results were able to offer the regression equation comprising the variables of cutting speed, feed rate, and depth of cut. It can be seen that this equation was employed for determining the optimal conditions for aluminum casting semi-solid 7075 in terms of surface roughness. From the analyses concerning the factors affecting surface roughness, the optimal conditions that corresponded to the minimum surface roughness of 0.34 µm. were the cutting speed of 220 m. min^{-1}, feed rate of 0.02 mm. rev^{-1}, and depth of cut of 0.45 mm. Thus, it can be concluded that the experiment for predicting the surface roughness provides accurate and reliable results. Furthermore, the wear mechanism was appeared with cutting speed, feed rate and depth of cut. The pattern of wear was similar to cracking of mechanical fatigue, such notch wear and crater wear.

5. Acknowledgement

This research was accomplished because of the budget provided by the 2016 annual government statement of expenditure, Rajamangala University of Technology Srivijaya. The material employed was provided by GISSCO Co., Ltd., of which is kindly acknowledged.

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