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SURFACE INTEGRITY EVALUATION ON ALUMINIUM-EPOXY COMPOSITE IN MACHINING USING TAGUCHI METHOD

The increasing needs of using aluminum epoxy composite as a replacement to solid metal rapid prototyping has opened to interests in optimizing its machining processes. This paper reported on the success of optimizing the surface roughness of aluminium epoxy composite using milling process along with a new finding on the best combination parameters. Taguchi method was used as the optimization method whereas spindle speed, feed rate, and depth of cut were set as input factors using an L9 Orthogonal Array. Analysis of Variance was used to identify the significant factors influencing the surface roughness. Experiment was conducted in dry condition using a vertical milling machine and the surface roughness after the machining was evaluated. Optimum combination of cutting parameters was identified after the finest surface roughness (response) based on the signal-to-noise ratio calculated. Cutting parameters selected after preliminary testing are cutting speeds of (2000, 3000 and 4000) rpm, feed rate (300, 400 and 500) mm/min, and cutting depth (0.15, 0.20, and 0.25) mm. The result showed that cutting speed had the largest percentage contribution to surface roughness with 69% and the second highest contribution was feed rate with 22% and depth of cut at 9%. The spindle speed was found as the most significant factor influencing the quality of surface roughness. The result is significant particularly in providing important guidelines for industries in selecting the right combination of parameters as well as to be cautious with the most significant factor affecting the milling process of metal epoxy composite.

Keywords: Hybrid Mold; Metal Epoxy composite (MEC); Machining; Injection Molding Process

1. Introduction

Aluminium-Epoxy Composite (AEC) has been widely used for a variety of applications such as rapid tooling, vacuum forming, rapid tooling for injection moulds and foundry. The material is frequently chosen due to its ease of use and high thermal and mechanical properties. Apart from that, AEC does not shrink visually during mould preparation process making it an extra advantage as compared to other materials in moulding industries [1]. An increasing demand on cheap long life of cutting tool of machining rapid tooling (RT) in particular, has led this material to become one of the potential candidates for injection moulding industries [1,2]. In addition to that, the use of this material has opened to numerous questions in terms of its machinability and life time as compared to metal. Although the materials can be pre-shaped according to the mould required, nonetheless secondary processes such as milling process is still needed in making sure the surface quality and dimensional accuracy of the AEC mould can conform to the specification [1]. This process is one of the most popular machining methods used for cutting or removing materials in transforming to desired shapes and is essential in many sectors particularly for fabricating injection moulds [2].

As RT always requires a high degree of surface finish, one of the concerns on post-milling processes is the quality of surface finish. This issue is amongst the concerns of using AEC as excessive and repetitive works on achieving desired surface quality, affecting the lead time and cost of products therefore must be taken care of by machinist when the processes take place [1]. In fact, the technical quality of any machined material is extensively defined by the surface finish; the out-of-range surface quality will be rejected; therefore, energy and time spent are excessively wasted. The average surface roughness parameter (Ra) is generally used as an indicative surface finish parameter. The Ra is reportedly affected by the geometry of the parameter

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settings and the present of coolant [3-6]. One of the best ways in determining the best combination parameter and the most significant factor that affects the quality of surface roughness is by using Taguchi Method [1].

Taguchi method is based in statistic an analysis of tests that can cut shorter time and can save cost to industries as it suggests an optimal design. The methods are originally based on the concepts of factorial-designs and orthogonal arrays. One advantage of this method is that multiple factors are considered at one time, including unnecessary noise factors [7-14]. In specific, this method has been widely used to optimize the most common controllable parameters, such as cutting speed, federate and depth of cut (DOC). In many studies of optimization method using Taguchi method involving milling operations, the surface roughness measurements are performed on the surface perpendicular to tool axis, usually horizontal or on both surfaces, perpendicular and parallel to tool axis, and is computed towards the average value [15-17].

There was an evidence on the analysis on metal fillers in epoxy [1] however the best combination parameters as well as the most significant parameter in minimizing the surface roughness after milling process is yet to explore. Hence, this work tried to analyze the level of each in put parameter influencing the results of surface roughness on parallel direction of tool axis for the end milling operation. The main goal was the determination of the optimal combination of milling parameters to in lowering the surface roughness value of AEC. The findings of this study are important to help mould and plastics making industries in selecting suitable parameters with appropriate parameter settings in the fabrication of mould inserts for the production of plastic parts using injection moulding process using AEC.

2. Methodology

2.1. Sample Preparation

A 30-wt% Aluminum filled epoxy and hardener was prepared with a dimension of 138 mm × 93.7 mm × 25.8 mm at room temperature. In preparing the samples, a plastic container acting as the mould of the same size was prepared for mixing process. The mixture of aluminium, epoxy and hardener were stirred for 15 minutes until the aluminium filler is uniformly distributed. The mixture was then de-gassed in a vacuum chamber for 60 minutes to remove any entrapped air from the samples. The final form of the aluminium reinforced epoxy sample is shown in Figure 1. All samples were prepared in our laboratory at Universiti Malaysia Perlis.

2.2. Parameter Selection and Taguchi Method

The first phase was defining three parameters with three levels. Spindle speed (cutting speed), feed rate, and depth of cut (DOC) was chosen as can be seen in Table1. Next, an L9 orthogonal array was chosen for experimental collection as represented in Table 2. This array was executed by slotting processes using Akira Seiki Performa SR3 XP CNC milling machine located at Universiti Malaysia Perlis, using HSS size 10 mm 4-fute end mill in dry condition, whereby the design of the experiments is shown in Table 3. The work piece sample underwent a facing process to remove the work piece from non-uniform surface. On CNC milling machine aluminium reinforced epoxy is used with four HSS end milling flutes of 10 mm. The work piece sample underwent a facing process to remove the work piece from any irregularities and non-uniform surface as shown in Figure 2. The fly cutter was then changed to the end mill and the machining operation was carried out according to the chosen machining parameters of the orthogonal array method as shown in Table 3. The surface profile of the machined region was inspected using Mitutoyo F-3000. The setting for speed of moveable electronic stylus was set as a 0.05 mm/s and the surface roughness, Ra was measured 3 times over the top of the slotted area one at the center and another two on the corner sides and with the three results were taken in averages as shown in Figure 4.

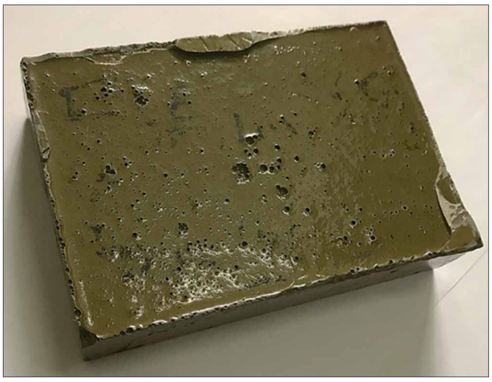


Fig. 1. AEC fabricated as samples for milling operations

TABLE 1

Selection of factor level for process parameters

Parameters	Units	Factor level		
		1	2	3
Cutting speed	RPM	1500	2000	2500
Feed Rate	mm/min	300	400	500
DOC	mm	0.15	0.20	0.25

TABLE 2

L9 orthogonal array

Trials	Parameters			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	1
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

TABLE 3

Design matrix and response of L9(3^3) Orthogonal Aray

No of Experiment	Cutting Speed (rpm)	Feed Rate (mm/min)	DOC (mm)
1	1500	300	0.15
2	1500	400	0.20
3	1500	500	0.25
4	2000	300	0.20
5	2000	400	0.25
6	2000	500	0.15
7	2500	300	0.25
8	2500	400	0.15
9	2500	500	0.20

The results from the Taguchi orthogonal array were then transformed into S/N ratio calculation using the Taguchi method using the smaller the better in predicting the optimal cutting output as desired on the surface roughness. The S/N ratio was determined in Equation 1, and the MSD was based on Equation 2.

$$S/N_s = -10 * \log(MSD) \tag{1}$$

$$MSD = \frac{1}{n}\sum_{i-1}^{n} y_i^2 \tag{2}$$

Where

y – the value of results

n – the number of the tests in one trial

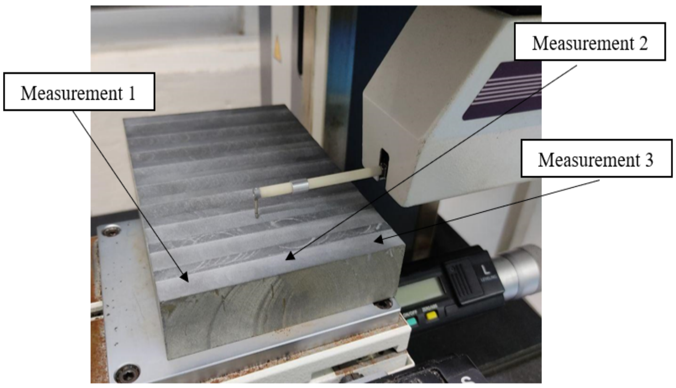
2.3. Analysis of Variance (ANOVA)

After Taguchi Method was successfully performed, ANOVA was employed to obtain the optimum conditions as required [18]. Minitab software was used to determine the percentage of impact variables. Example of calculation is as elaborated in previous manuscript [19-21].

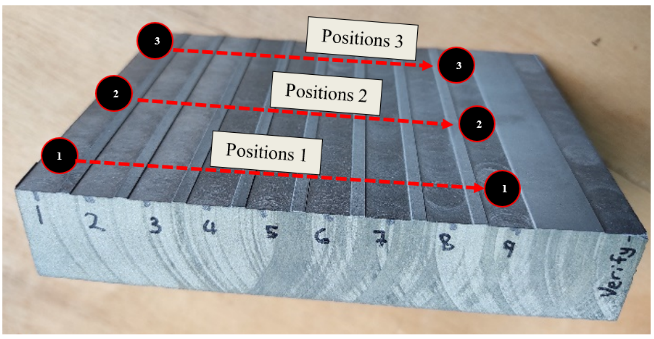
3. Results and discussion

The surface roughness data acquired after the experiment is shown in Table 4 using surface roughness tester. The lowest surface roughness, Ra was found at Experiment 1 with 0.619 µm based on 1500 rpm with 300 mm/min feed rate and 0.15 mm DOC. On the other hand, experiment 7 contributed to the highest level of Ra at 0.923 µm with parameters 2500 rpm, 300 mm/min, and 0.25 mm DOC. The most remarkable result observed was that the increasing cutting speed reduces the quality of surface roughness which is in line with previous reports [19-21]. This situation happened due to the fact that it generates large burr quantity on the machined surface, consequently deteriorating surface finish. This phenomenon is associated with growth on the cutting forces and as a result leading to dynamic instability to the cutting process [20]. Machining in dry conditions with specific combinations of parameters created differences in the average surface roughness, Ra value. For Experiment 3,

(a)



(b)



(c)

Fig. 2. (a) Aluminium Epoxy sample after undergoing facing process, (b) Position of Ra measurement using Mitutoyo F-3000, and (c) Samples after slotting the process and the positions of where the Ra measurement was taken for all 9 slots

the use of the smallest cutting speed, 1500 rpm, but with maximum cutting depth and feed rates 0.25 mm and 500 mm/min causes poor surface roughness as compared to Experiment 1. It can be seen from the results of the 9 experiments that cutting speed was not the only parameter that influences the surface quality. Although cutting speed increases, however the surface quality was found poorer throughout the 9 experiments as there were changes of feed rate in particular that led to the deterioration of surface quality.

TABLE 4

Experimental results after undergoing L9 Taguchi Method

Experiment No	Cutting Speed (rpm)	Feed Rate (mm/min)	DOC (mm)	Ra (μm)
1	1500	300	0.15	0.619
2	1500	400	0.20	0.640
3	1500	500	0.25	0.818
4	2000	300	0.20	0.726
5	2000	400	0.25	0.735
6	2000	500	0.15	0.858
7	2500	300	0.25	0.923
8	2500	400	0.15	0.823
9	2500	500	0.20	0.745

3.1. Signal-to-Noise Ratio

The S/N ratio was employed rather than the standard deviation as a measurable data since the standard deviation often deceases as either the mean decreases and vice versa [21-24]. In this way, it is no more a requirement to reduce the standard deviation first and get the average to the target in the same way as previously discussed in the literature whereby the target mean value varied during the process development [25]. Figure 3 shows the effect Signal to Noise (S/N) ratios in which for every parameter, the highest value was selected and the desired value towards minimizing the surface roughness was 1500 rpm, feed rates at 400 mm/min, whereas the DOC was at 0.2 mm.

A low cutting speed of 1500 rpm contributed to achieving a better surface roughness as fewer vibrations was experienced as compared to higher cutting speeds [15]. Table 5 shows the response table for S/N ratios and the ranks of cutting parameters, which mainly affected the surface roughness. From the table, the cutting speed was found to be the most significant factor contributing to the results of surface roughness in the maximum S/N ratio of 1.608, and the second highest parameter was the DOC at 1.367 S/N value, and feed rate was found to be the lowest factor. This important result indicates that machinist must be ready to take care of the cutting speed parameter as small changes can lead to big differences on the surface quality of AEC. Table 6 shows the summary of ANOVA results and summarizes the details relevant to the analysis of variances and the case statistics for further clarification.

TABLE 5

ANOVA Responses for Signal to Noise Ratios

Level	Cutting peed	Feed Rate	DOC
1	3.260	2.547	2.396
2	2.263	2.750	3.073
3	1.652	1.877	1.706
Delta	1.608	0.873	1.367
Rank	1	3	2

From Table 6 and by referring to the F-value for the cutting speed, feed rate and DOC. The level of significant value is $F_{0.05,2,2}$ = 19.00, parameters for the all F-value are not more than the confident interval, F-value < 19.00 indicating that the

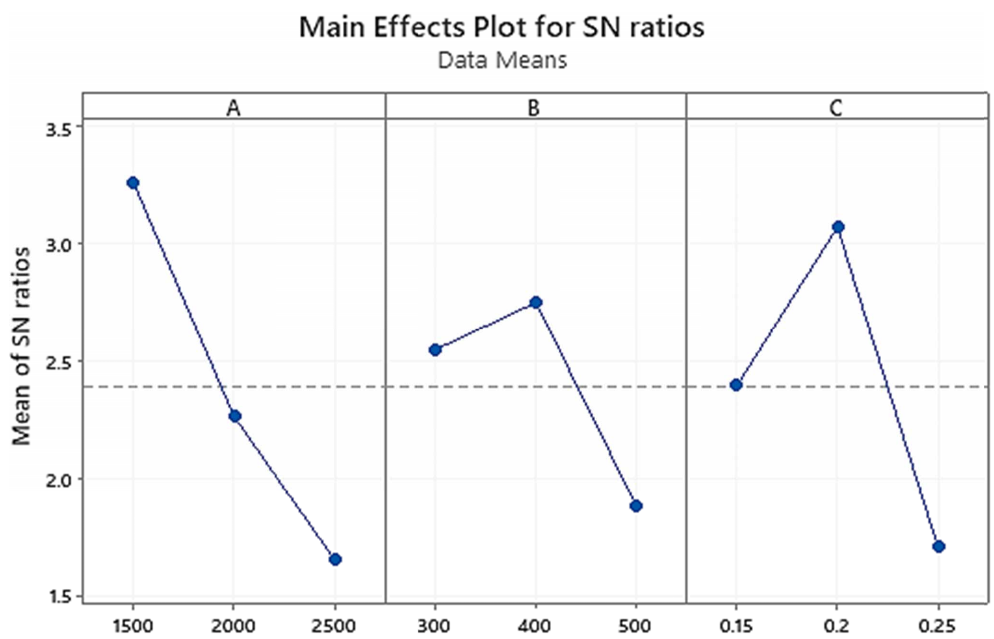


Fig. 3. Data graph for main effect S/N ratios

validated result for the three factors are no significant of that response. It is assumed in this way because of the gap for each result with respect to the average surface roughness is too close amounting to nearly 0.3 mm. This value can affect significantly and because the value of the parameter itself is too close.

TABLE 6

ANOVA Results analyzed from results in Taguchi Method

Variance	Degree of Freedom (DoF)	Sum of Square (SS)	Mean Square (MS)	F-value	Contribution Rate (%)
Cutting Speed (rpm)	2	0.0286	0.01430	1.44	48.00
Feed Rate (mm/min	2	0.0087	0.00435	0.44	14.67
DOC (mm)	2	0.0222	0.011107	1.12	37.33
Residual Error	2	0.0198	0.00992	—	
Total	8	0.0794		3	100%

3.2. Improvement analysis

From the first experiment result, all F-values were not more than the level of significance indicating that all parameters caused had no substantial consequences on the quality of the surface profile. This is referred to the previous research and therefore it was decided that the value of the cutting speed must be adjusted to clear the level of the significance [8]. The experimental findings showed that the cutting speed affected on the surface were greater than that of cutting depth and the feed rate for the milling process [8]. On the second time, another improvement analysis was made with experimental design for the L9 orthogonal array as shown in Table 7 and the milling process was performed using the same CNC milling. Results of the improved data is shown in Table 8 in which 2000 rpm was the minimum range of cutting speed, producing the smallest value with 4000 rpm leading to the poorest surface roughness. An increase in cutting speed from 2000 rpm, 3000 rpm, and 4000 rpm resulted in an improve the surface roughness. This proves that cutting speed does affect the roughness surface of the AEC.

For the feed rate, the difference value from 300 mm/min until 500 mm/min was divided into three parts. The increased value of the feed rate also increases the surface roughness for all numbers of an experiment. For example, experiment five and six feed rates are 400 mm/min and 500 mm/min the result is 0.69 µm and 0.99 µm. But on the experiment number two and three, there was only a slight decrease for the surface roughness which are 0.748 µm and 0.719 µm with same cutting speed 2000 rpm. The temperature between both the machining interfaces is more sufficient at low cutting speed to build the greater BUE (Built up edge) and even the fracturing of chips that quickly generate the rough surface, which can cause adhesive wear on the instrument. As the cutting speed raises, the processing time of machining reduces and eliminates the BUE, decreasing the chip formation, and also its roughness.

In experiments 8 and 9 on the surface roughness, Ra is measured at 1.156 µm and 1.215 µm. As the DOC increases from 0.15 mm to 0.20 mm, the average roughness of the surface was also found increases. But some number in the experiment was less affective when reducing the value of DOC such as experiment five to eight having values from 0.25 mm to 0.15 mm which indicates having less effect. Figure 4 shows the S/N ratio graph showing the best parameter with high value of cutting speed at 2000 rpm, feed rates (300 mm/min) and DOC at 0.25 mm. A low surface roughness was found at using low cutting speed of 2000 rpm compared to 3000 rpm and 4000 rpm on the aluminum epoxy showed similar results as compared to the first experiment

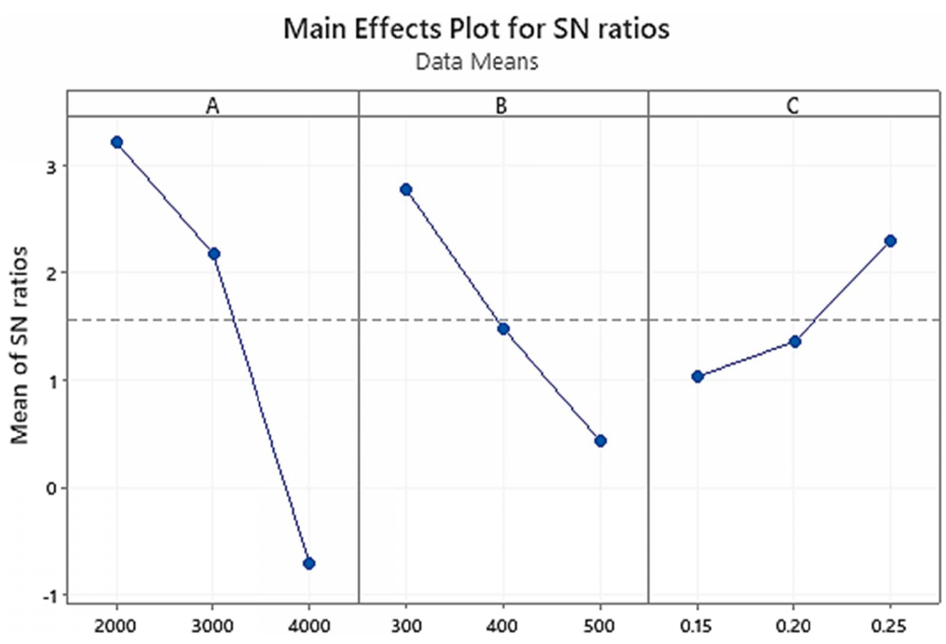


Fig. 4. Main effect S/N ratios data graph

that is low cutting speed was the found the best. This result was experienced due to the face that fewer vibrations was happening, leading to better surface finish.

TABLE 7

Design matrix for L9 orthogonal array

No. of Experiment	Cutting Speed (rpm)	Feed Rate (mm/min)	DOC (mm)	Cutting Condition
1	2000	300	0.15	dry
2	2000	400	0.20	dry
3	2000	500	0.25	dry
4	3000	300	0.20	dry
5	3000	400	0.25	dry
6	3000	500	0.15	dry
7	4000	300	0.25	dry
8	4000	400	0.15	dry
9	4000	500	0.20	dry

TABLE 8

Surface roughness experiment data

No. of Experiment	Cutting Speed (rpm)	Feed Rate (mm/min)	DOC (mm)	Ra (μm)
1	2000	300	0.15	0.611
2	2000	400	0.20	0.748
3	2000	500	0.25	0.719
4	3000	300	0.20	0.689
5	3000	400	0.25	0.690
6	3000	500	0.15	0.987
7	4000	300	0.25	0.911
8	4000	400	0.15	1.156
9	4000	500	0.20	1.215

Analysis of Variance (ANOVA) was carried out to determine the effect of machining parameters on surface roughness as shown in Table 9. The significance level obtained in this study is $F_{0.05,2,2} = 19.00$ at the confidence level equals to 0.05. The results present the most significant factors which are cutting speed and the value is [$F_{statistic}$ data = 79.47 > 19.00] as compared to all feed rates and DOCs. The next significant factor was feed rate [$F_{statistics} = 25.63 > 19.00$] having low contribution on the surface roughness at 22.15% and lastly, the DOC was found to have the least effect of the surface roughness [$F_{statistics} = 10.63 < 19.00$] with 9.19%.

TABLE 9

Summary of Analysis of Variance (ANOVA)

Source of Variance	Degree of Freedom (DF)	Sum of Square (SS)	Mean Square (MS)	F-value	Contribution Rate (%)
Cutting Speed (rpm)	2	0.26136	0.13068	79.47	68.67
Feed Rate (mm/min	2	0.08429	0.04215	25.63	22.15
DOC (mm)	2	0.03496	0.01748	10.63	9.19
Residual Error	2	0.00329	0.00164	—	
Total	8	0.38389		115.73	

3.3. Verification Test

The verification test was carried out after the initial evaluation process. This stage was employed to ensure the theoretical optimum results are verified with the real test whether they are acceptable, valid, and robust. At the end of ANOVA analysis, a confirmation test is generally essential to eliminate concerns about the choice of control parameters, the way the experiment was designed as well as assumptions that have been made throughout this analysis [26-29]. The parameters used in confirmatory tests have been applied by Minitab software. Recommendation setting parameters were 2000 rpm for cutting speed, 300 mm/min for the feed rate and DOC was set at 0.15 mm. The result confirmation test is shown in Table 10 in which highlighting that the best parameters was used to run the experiment to check the verification. The value surface roughness from this validation test is 0.609 μm as compared to the nine number of experiments especially experiment number one that is the lowest value 0.611 μm.

TABLE 10

Surface roughness confirmation test result

Parameters			Ra
Factor	Level	Setting	0.609 μm
Cutting Speed (RPM)	1	2000	
Feed Rate (mm/min)	1	300	
DOC (mm)	3	0.25	

The findings were then compared with the calculated result, in finding the ideal variable predicted was justifiable. The percentage of error between the prediction and simulation results was calculated using Equation 3 and the result was only 5.36%, which is acceptable as it is below than 10%. Therefore, the error percentage by less than 10% has been shown to be acceptable and reliable and even the actual results of the confirmatory test were quite higher than the estimated. The findings are also reliable [20].

Percentage of Error (%) =

$$Error = \frac{Experimental - Calculated\ Results}{Calculated\ Results} \times 100\%$$

$$Error = \frac{0.609 - 0.578}{0.578} \times 100\% = 5.36\% \tag{3}$$

5. Conclusion

It can be concluded that to optimize milling parameters of parameters, the best cutting parameter is cutting speed at 2000 rpm with a feed rate of 300 mm/rev and a cutting depth of 0.25 mm. The result shows that the cutting speed is the most significant factor influencing aluminum epoxy surface roughness. Thus, the feed rate is the least important factor and the last factor was the DOC affecting surface roughness of the AEC.

From the contribution rate, cutting speed shows the highest-level contribution on the surface roughness at 68.67%, followed by feed at 22.15% and last cutting depth at 9.19%.

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