MACHINING OF POLYETHELENE-ALUMINUM COMPOSITE FROM USED BEVERAGE CARTON WASTE BY MILLING USING HIGH-SPEED CUTTING TOOLS

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ABSTRACT

The waste from used beverage cartons consisted of a layer of paper and multi-layer film that consist of polyethylene and aluminum foil. They were classified as orphaned waste and they can be developed as polyethylene aluminum composite material called "PolyAl". This research aimed to study the machining procedures of PolyAl from used beverage cartons by milling with high-speed cutting tools. The single screw extruder was used for producing the PolyAl pellet. They were pressed to form a square plate size 300 x 300 mm^2 and a thickness of 10 mm. These composite plates were cut into a small square plate with a size of 55 x 55 mm^2 with a thickness of 10 mm. They were used for milling on 3-axis CNC with high-speed cutting tools and measuring the surface roughness (Ra). The objective was to investigate machining in terms of the effect of two types of high-speed cutting tools: 2 and 4 flutes, and the factors of machining consist of feed rate, spindle speed and depth of cut. The design of experiment (DOE) was carried out to design experiments of General full factorial. The results of the machining by 2 flutes high speed end mill founded that Ra increases with increasing feed rate, Ra decreases with increasing spindle speed, and Ra tends to decrease with increasing depth of cut. The machining by 4 flutes high speed end mill founded that Ra increases with increasing feed rate, Ra decreases with increasing spindle speed and Ra tends to decrease with increasing depth of cut. The optimal condition of 2 flutes high speed end mill was Ra of 1.914 um with following conditions: a feed rate of 400 mm/min, a spindle speed of 1500 rpm and a depth of cut of 1 mm, and the optimal condition of 4 flutes high speed end mill was Ra of 2.385 um with following conditions: a feed rate of 1000 mm/min, a spindle speed of 1500 rpm and a depth of cut of 3 mm.

1 INTRODUCTION

Now a days, the problem of plastic waste from everyday life has greatly affected on environment, causing damage to the natural system. The 2020 recycling data of used beverage cartons (UBCs) in Thailand were summarized by Tetra Pak (Thailand) Co., Ltd. [1]. It was found that UBCs wastes left from consumption only about 5.9 percent. The ultra-high-temperature (UHT) packaging consists of 6 layers: 1) polyethylene to prevent moisture from outside, 2) paper for durability of the box, 3) polyethylene helps seal the box tightly, 4) aluminum foil prevents external conditions, 5) polyethylene helps seal the box tightly and 6) polyethylene helps prevent and adhere to the leak of liquid [2].

In the recycling process, UBCs were defiberized by mechanical spun, and the paper pulp was separated and recycled as shown in Fig. 1. Meanwhile, the multi-layer film of polyethylene and aluminum foils remained difficult to recycle. It is challenging for the researcher to find out the various applications of these materials. In this research, polyethylene and aluminum foils were compounded and transformed into pellets and powder which appropriated with various processes such as injection molding, compression molding and rotational molding. Generally, these processes typically require specialized molds and manufacturing machines. In addition, it is essential to form a mold that affects the high cost and takes a lot of time to produce the identity products with a small amount. Furthermore, the production volume needs to be large in order to have reasonable production costs. From these problems, it is difficult to produce identity products in small amounts or produce prototype products. The waste from used beverage cartons consisting of a multi-layer plastic film composed of aluminum foil and has a texture similar to terrazzo stone with glittering aluminum flakes throughout with good mechanical properties, lightweight, and easy to move. They are suitable for use as decoration materials. As previously mentioned, it is costly to produce the product with a metal mold. Therefore, this research has the objective of solving this problem by machining PolyAl into various shapes as the designing. Milling with high-speed tool are interesting for solving this problem.

This work focused on the effects of milling machining conditions on the surface roughness of PolyAl composites as important data for manufacturing with basic machining processes with low-cost cutting tools. This information will be a set of basic data that recommends the user who is interested to use PolyAL to produce the product with a small amount or prototype for a specific application. It also contributes to promoting the consideration of using recycled materials to produce real pieces with basic technology, and low production costs that obtain a potential prototype or ready-to-use products. Moreover, it will help and contribute to the preservation of the plastic waste solution by corresponding to the environmental policy and the circular economy policy of the Thai government to achieve the sustainability of the entire economy and reduce pollution to the environment

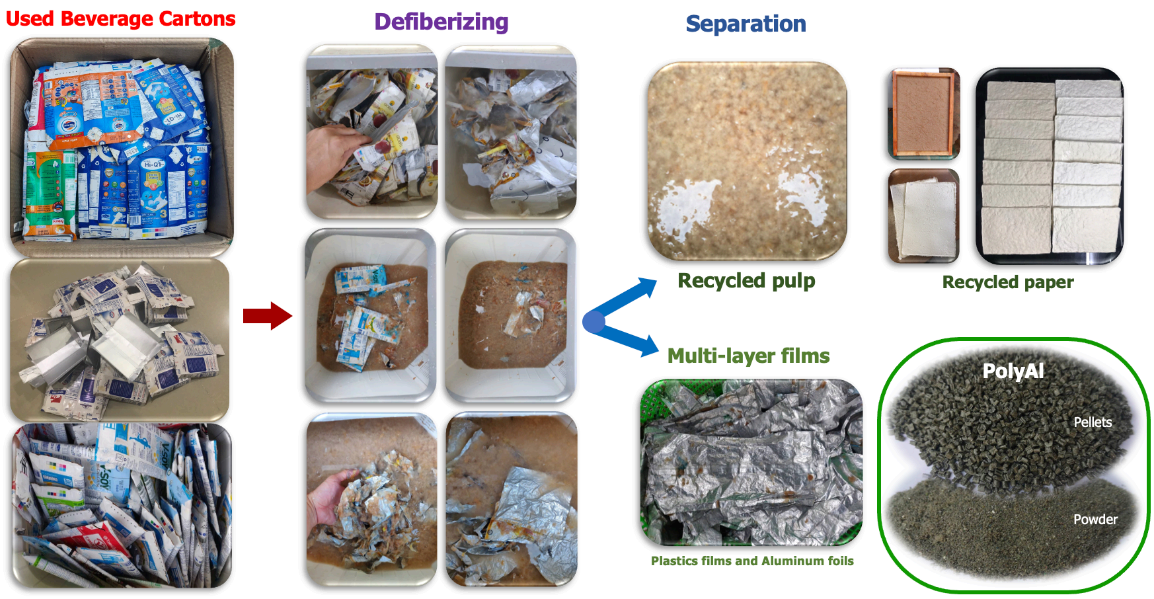
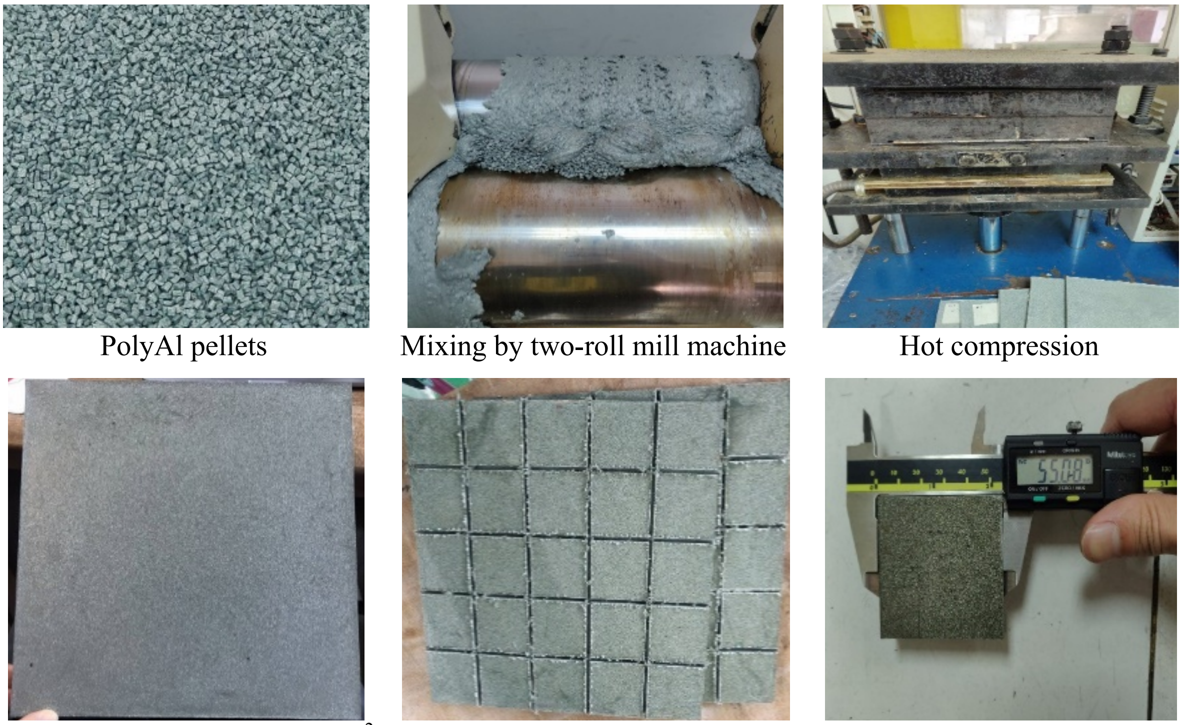


Fig 1: Recycling process of used beverage cartons (UBCs)

2 MATERIALS AND METHOD

2.1 Materials preparation

The multi-layer film of polyethylene and aluminum foils was compounded by using a single-screw extruder and transformed into PolyAl pellets with a diameter of 2 - 4 mm and a length of 5 mm. These PolyAl pellets were melted and mixed with the two-row mill before being compressed to a square plate a size of 300 x 300 mm^2 and a thickness of 10 mm. They were compressed with a pressure of 10 MPa and a temperature of 200 °C for 25 min and subsequently cooled down to room temperature. These composite plates were cut into a small square plate with a size of 55 x 55 mm^2 and a thickness of 10 mm. The preparation of specimens are shown in Fig. 2.



PolyAl pellets | Mixing by two-roll mill machine | Hot compression

Composite sheet: 300 x300 mm^2 | Cutting | Specimen with a size of 55 x55 mm^2

Fig 2: The preparation of specimens for milling with high-speed cutting tools.

2.2 Milling machine and cutting tools

The 3-axis CNC milling machine in this experiment is shown in Fig. 3. PolyAl specimens were cut by the high-speed end mill with a diameter of 6 mm of 2 and 4 flutes as shown in Fig. 4.

Fig 3: The 3-axis CNC milling machine (Eumach LMC 850)

Fig 4: High-speed end mill with a diameter of 6 mm of 2 and 4 flutes

Table 1 Cutting conditions for machining testing

Parameter	Level 1	Level 2	Level 3
Spindle speed (rpm)	500	1000	1500
Feed rate (mm/min)	400	1000	1600
Depth of cut (mm)	1	3	6

2.3 Surface roughness test

In surface roughness measurement, the value of surface roughness (Ra) was measured by a surface roughness tester (Mitutoyo SJ-411) as shown in Fig.5. The surface of the end mill groove was conducted for measuring of Ra and the position of measuring is shown in Fig. 6. A length of surface roughness measuring was 4 mm in each test.

Fig 5: Surface roughness tester (Mitutoyo SJ-411

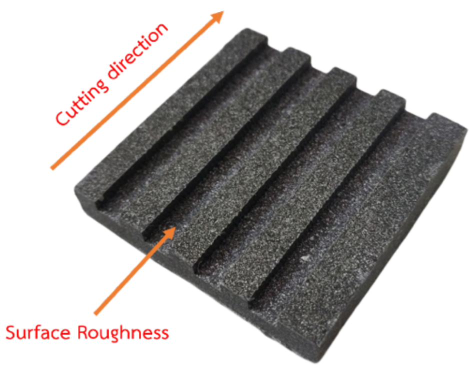


Fig 6: Position of measuring the surface roughness

2.4 Design of Experiment (DOE)

In the experiment, milling parameters consisted of spindle speed, feed rate, and depth of cut that is used to design by DOE. The general full factorial experiment was designed by Minitab 18 software, and the result was carried out by statistical analysis. The design consists of spindle speed (A) 3 level, feed rate (B) 3 level, and depth of cut (C) 3 level for measuring Ra (Y) as shown in Table 1. From DOE, there were measurements in 54 experiments with 4 replicates which were divided into 27 experiments for different cutting tools. The hypothesis test was used for investigation of the interaction between spindle speed, feed rate, and depth of cut, which H0: the factors that have affected Ra, and H1: the factors that have not affected Ra. The significance level (α) was determined as 95% or 0.05.

3. RESULTS AND DISCUSSION

In this experiment, PolyAl composite samples were investigated using Ra to determine the optimal machining parameters. To achieve the best results when machining PolyAl products, it is crucial to determine the ideal parameters that could affect Ra.

Tables 2 and 3 show information on surface roughness (Ra) for end mill 2 and 4 flutes with different parameters. The samples were analyzed consistently, and the results were reported through statistical measures, including mean and standard deviation values. To identify the parameters that impact Ra, various Ra results with different parameters were compared using normal probability, versus order, and versus fits analysis. The main effect was compared, and conditions were optimized accordingly.

Table 2: Surface roughness (Ra) using a 2-flute end mill with different parameters.

No.	Feed rate (mm/min)	Spindle speed (rpm)	Depth of cut (mm)	Ra (µm)	SD
1	400	500	1	4.67	0.59
2	400	500	3	4.00	0.39
3	400	500	6	4.39	0.24
4	400	1000	1	2.85	0.26
5	400	1000	3	3.19	0.51
6	400	1000	6	3.21	1.47
7	400	1500	1	4.17	0.19
8	400	1500	3	2.54	0.23
9	400	1500	6	3.06	0.49
10	1000	500	1	4.46	0.34
11	1000	500	3	4.01	0.37
12	1000	500	6	4.18	0.44
13	1000	1000	1	3.89	0.25
14	1000	1000	3	3.21	0.34
15	1000	1000	6	3.09	0.62
16	1000	1500	1	4.04	0.29
17	1000	1500	3	2.39	0.27
18	1000	1500	6	3.24	0.17
19	1600	500	1	6.26	1.00
20	1600	500	3	4.97	0.46
21	1600	500	6	3.39	0.51
22	1600	1000	1	3.69	0.37
23	1600	1000	3	2.88	0.59
24	1600	1000	6	3.66	0.46
25	1600	1500	1	3.71	0.46
26	1600	1500	3	2.65	0.14
27	1600	1500	6	3.44	0.79

Table 3: Surface roughness (Ra) using a 4-flute end mill with different parameters.

No.	Feed rate (mm/min)	Spindle speed (rpm)	Depth of cut (mm)	Ra (µm)	SD
1	400	500	1	4.67	0.55
2	400	500	3	3.90	0.30
3	400	500	6	5.69	0.67
4	400	1000	1	2.85	0.71
5	400	1000	3	3.19	0.39
6	400	1000	6	3.21	0.82
7	400	1500	1	4.96	0.15
8	400	1500	3	2.54	0.48
9	400	1500	6	3.06	1.21
10	1000	500	1	4.46	0.49
11	1000	500	3	4.01	1.30
12	1000	500	6	4.18	0.48
13	1000	1000	1	3.89	0.16
14	1000	1000	3	3.21	0.59
15	1000	1000	6	3.09	0.47
16	1000	1500	1	4.04	1.25
17	1000	1500	3	2.39	0.30
18	1000	1500	6	3.24	1.11
19	1600	500	1	6.26	0.82
20	1600	500	3	4.97	2.53
21	1600	500	6	3.39	0.92
22	1600	1000	1	4.16	0.12
23	1600	1000	3	2.88	0.39
24	1600	1000	6	4.04	0.32
25	1600	1500	1	3.71	0.36
26	1600	1500	3	2.65	0.26
27	1600	1500	6	3.44	0.43

Figures 7 and 8 display the plots of normal probability versus fits, versus order, and histogram. These plots provide evidence that the Ra from using 2 and 4-flute end mills follows a normal distribution and has constant variances, has constant variance which is in accordance with the previous reported results in [7-8].

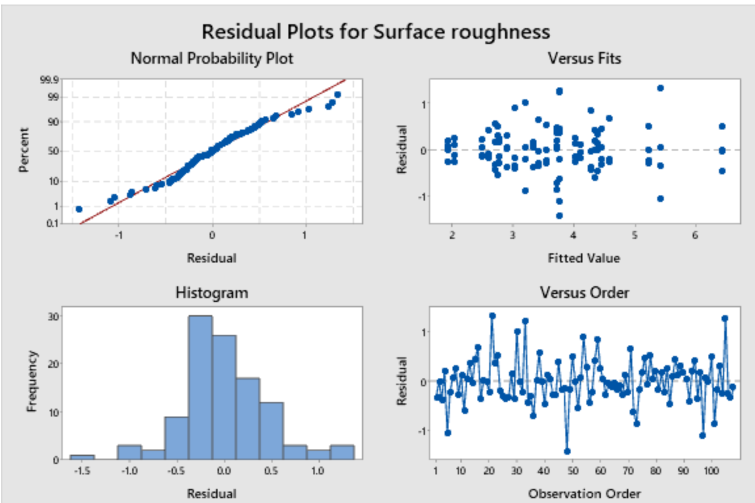


Fig 7: Ra residual plots using the 2-flute end mill.

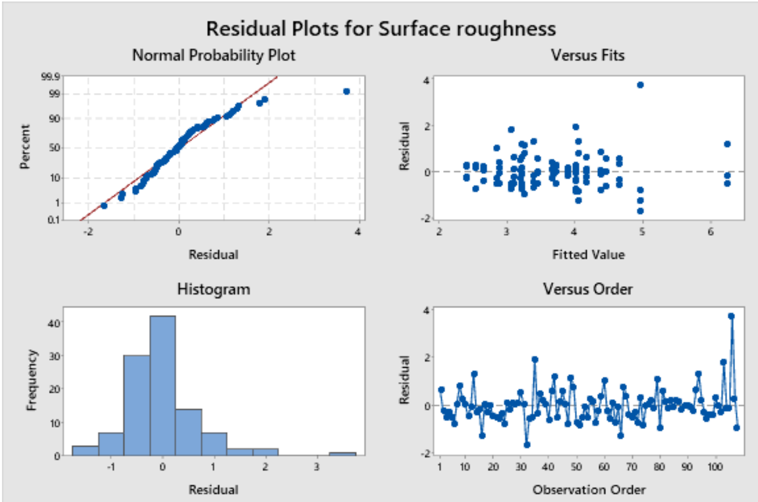


Fig 8: Ra residual plots using the 4-flute end mill.

In Table 4, an examination of Ra using the 2-flute end mill with a statistical significance of 0.05 (α) revealed that the p-value of univariate data including feed rate, spindle speed, and depth of cut, was less than 0.05. The p-values for the covariate of the 2 and 3-parameter interactions were found to be similar [7]. These findings indicate that the parameters are independent, and effective on Ra according to the H_0 hypothesis.

Table 4: Analysis of Ra variance using a 2-flute end mill.

Source of variation	DF	Adj SS	Adj MS	F-value	P-value
Feed rate (mm/min)	2	3.368	1.684	5.98	0.004
Spindle speed (rpm)	2	66.381	33.191	117.79	0.000
Depth of cut (mm)	2	15.371	7.686	27.27	0.000
Feed rate (mm/min)* Spindle speed (rpm)	4	4.832	1.208	4.29	0.003
Feed rate (mm/min)* Depth of cut (mm)	4	4.582	1.145	4.07	0.005
Spindle speed (rpm)* Depth of cut (mm)	4	4.619	1.154	4.10	0.004
Feed rate (mm/min)* Spindle speed (rpm)* Depth of cut (mm)	8	15.904	1.988	7.06	0.000
Error	81	22.824			
Total	107	137.881			

S = 0.530829 R-Sq = 83.45% R-Sq(adj) = 70.57%

Table 5: Analysis of Ra variance using an end mill 4 flute

Source of variation	DF	Adj SS	Adj MS	F-value	P-value
Feed rate (mm/min)	2	1.723	0.861	1.29	0.282
Spindle speed (rpm)	2	35.126	17.563	26.24	0.000
Depth of cut (mm)	2	15.156	7.578	11.32	0.000
Feed rate (mm/min)* Spindle speed (rpm)	4	2.048	0.512	0.77	0.551
Feed rate (mm/min)* Depth of cut (mm)	4	1.619	0.404	0.60	0.660
Spindle speed (rpm)* Depth of cut (mm)	4	6.575	1.644	2.46	0.052
Feed rate (mm/min)* Spindle speed (rpm)* Depth of cut (mm)	8	11.436	1.430	2.14	0.041
Error	81	54.207	0.670		
Total	107	127.89			

S = 0.818 R-Sq = 57.61% R-Sq(adj) = 44.01%

The p-value of Ra using a 4-flute end mill presents different results as shown in Table 5. The individual univariate feed rate was 0.282, over the statistical significance. The covariate variables of interactions between feed rate and spindle speed, feed rate and depth of cut, and spindle rate and depth of cut were 0.551, 0.660, and 0.052, respectively. Upon analysis, it was found that both univariate and covariate variables are interdependent and have no significant effect on Ra, which supports the H_1 hypothesis.

The main effects plots of Ra using 2 and 4-flute end mills are presented in Fig. 9 and 10. The figures show that Ra increased with an increase in feed rate, but decreased with an increase in spindle speed. Likewise, literature [3], Azmi bi [4], Das [9], and Kumar [10] explained that an increase in feed rate affected Ra due to the increasing vibration of the cutting tool on a sample. Meanwhile, Abdullah [11] explained that an increase in spindle speed creates a higher temperature on the sample, making the material easy to cut, and decreasing Ra.

Considering the depth of cut, Ra using the 2-flute end mill increased at 3 mm depth but decreased at 6 mm depth. Ra using the 4-flute end mill decreased at 3 mm depth but slightly increased at 6 mm depth.

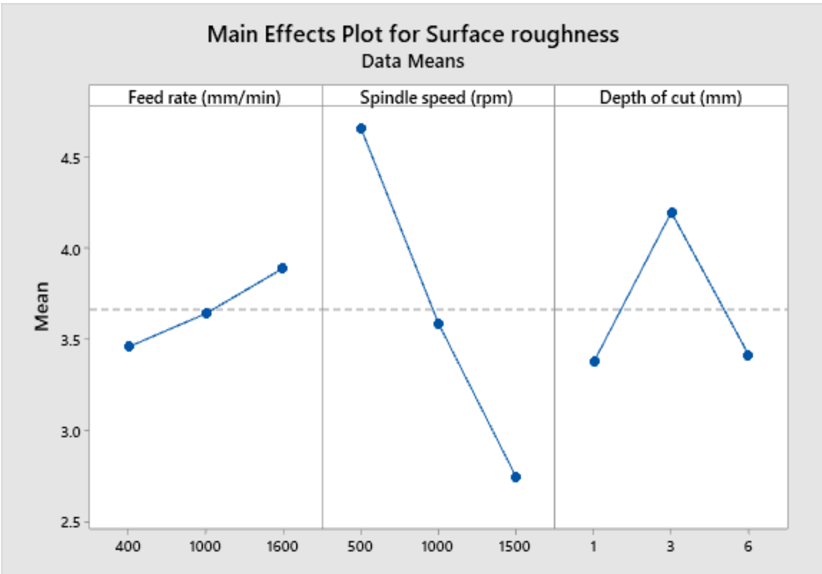


Fig 9: Main effect plot of Ra using a 2-flute end mill.

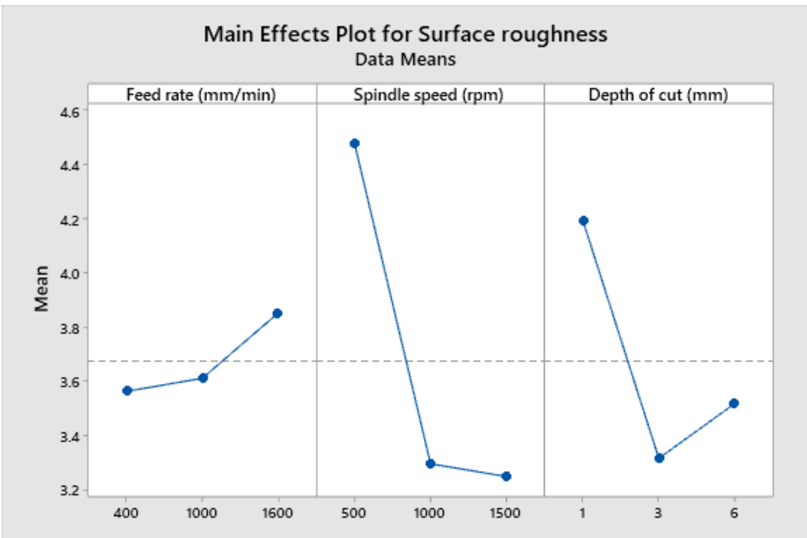


Fig 10: Main effect plot of Ra using a 4-flute end mill.

Table 6 shows an analysis of the optimal condition. The 2-flute end mill was optimized at Ra of 1.914 µm with 400 mm/min feed rate, 1500 rpm spindle speed, and 1 mm. depth of cut. The 4-flute end mill was optimized at Ra of 2.38 µm with 1000 mm/min feed rate, 1500 rpm spindle speed, and 3 mm depth of cut.

Table 6 The optimized conditions of the 2 and 4-flute end mill.

High-speed end mill	Feed rate(mm/min)	Spindle speed(rpm)	Depth of cut (mm)	Ra
2-flute	400	1500	1	1.91
4-flute	1000	1500	3	2.38

When comparing the optimized cutting conditions of 2 and 4-flute end mills, the results showed that the cutting using the 2-flute end mill resulted in a smoother surface. Corresponding with general data [12], the 2-flute end mill is designed explicitly with 2-wide flutes and it has a wide chip breaker area to help evacuate the chipping material. Therefore 2-flute end mill is suitable for milling soft materials and results in a smoother surface. The specialized 4-flute end mill is designed with 4 general flutes suited to operate at high spindle speeds, making it ideal for hard materials but this end mill has poor evacuate the chipping material. Meanwhile, cutting PolyAl with high speed might result in the increase in the high temperature that occurred in the melt area of the polymer. The results obtained using 2 flutes were preferable to those achieved with 4 flutes. This is because the design of the 2-flute end mill is well-boasting a superior chip breaker and suited for the hardness of PolyAl. This indicates that the 2-flute end mill can be used for the PolyAl cutting machine, like other general materials. Fig. 11 shows the sample of 3D wall from PolyAl that was milled by high-speed end mill.

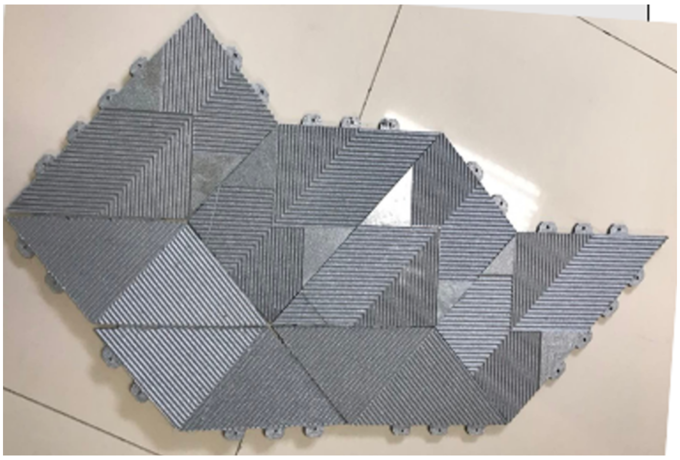


Fig. 11: Sample of 3D wall from PolyAl that was milled by high-speed end mill.

4. CONCLUSION

This work investigated the effects of using a 3-axis CNC milling machine with end mills of 2 and 4 flutes on the Ra for 3D PolyAl composite machining. The samples were cut under cutting conditions with different parameters of feed rate, spindle speed, and depth of cut. After statistical analysis using the DOE, all parameters considering univariate and covariates interactions using the 2 flutes were effect Ra. By investigating using 4 flutes, the feed rate was interdependent, and the covariate interactions were also interdependent and ineffective to Ra. The Ra continually analyzes considering the main effect reliable and accruable revealed that feed rate and spindle speed were effective to the PolyAl surface roughness when machining. The results showed optimized condition Ra at 1.914 µm of the 2-flute end mill with 400 mm/min feed rate, 1500 rev/min spindle speed, and 1 mm. depth of cut because of the efficient chip breaker. Therefore, a 3-axis CNC milling machine with a 2-flute end mill can use for machining 3D wall of PolyAl composite.

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