

The optimization study on the tool wear of carbide cutting tool during milling Carbon Fibre Reinforced (CFRP) using Response Surface Methodology (RSM)

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Abstract. Carbon Fibre Reinforced Plastic (CFRP) composite has become one of famous materials in industry, such as automotive, aeronautics, aerospace and aircraft. CFRP is attractive due to its properties, which promising better strength and high specification of mechanical properties other than its high resistance to corrosion. Other than being abrasive material due to the carbon nature, CFRP is an anisotropic material, which the knowledge of machining metal and steel cannot be applied during machining CFRP. The improper technique and parameters used to machine CFRP may result in high tool wear. This paper is to study the tool wear of 8 mm diameter carbide cutting tool during milling CFRP. To predict the suitable cutting parameters within range of 3500-6220 (rev/min), 200-245 (mm/min), and 0.4-1.8 (mm) for cutting speed, speed, feed rate and depth of cut respectively, which produce optimized result (less tool wear), Response Surface Methodology (RSM) has been used. Based on the developed mathematical model, feed rate was identified as the primary significant item that influenced tool wear. The optimized cutting parameters are cutting speed, feed and depth of cut of 3500 rev/min, 200 mm/min and 0.5 mm, respectively, with tool wear of 0.0267 mm. It is also can be observed that as the cutting speed and feed rate increased the tool wear is increasing.

1. Introduction

CFRP is an expensive Fibre Reinforced Plastic (FRP) which is very favourable material especially in aircraft industrial due to their mechanical and physical properties. The combination of the matrix and fiber reinforcement at high strength levels in engineering components provides high fracture toughness, high specific stiffness, excellent in creep, and corrosion and thermal resistance. It is also stronger than steel and stiffer than titanium while retaining its lighter weight compared to conventional single-phase materials. As the applications for CFRP composites expand in various fields, the parameters for machining have also diversified. The necessity for machining arises as CFRP parts are produced near-net-shape, a process that eliminates rough machining operations. Thus, machining operations such as milling is still necessary to give the CFRP parts their final shape [1,2,3].



In spite of growing demand and usage, problems have arisen with CFRP in terms of machining. Knowledge and experience acquired for conventional materials cannot be applied to these newer materials. It has been reported that machining CFRP is not only difficult to handle because of its inhomogeneity and anisotropic structure, but also because of its abrasive nature which comes from the carbon, and that aspects differ from metal [4,5]. In general, the challenges face during machining CFRP can be classified into two which are excessive tool wear and surface quality [1]. Unlike metal, it has been reported that machining CFRP not only involved the tool edge chipping but also the excessive abrasive wear due to the high strength carbon fibers [3, 5]. Those machining difficulties make machining CFRP time-consuming and expensive. To achieve high productivity and associated cost reduction, many approaches have been attempted such as finding the optimization of machining CFRP via modeling as it is necessary to understand the mechanics of the process and to improve the machinability of CFRP [7].

2. Experimental Materials and Methodology

The milling process was performed on the unidirectional CFRP with dimensions of 200 x 200 x 3 mm. CFRP panel, which was made using vacuum bagging method was illustrated in Figure 1. The material of panel includes the mixing 58% of carbon fibres and 42% of resin. The detailed of physical properties was shown in Table 1.

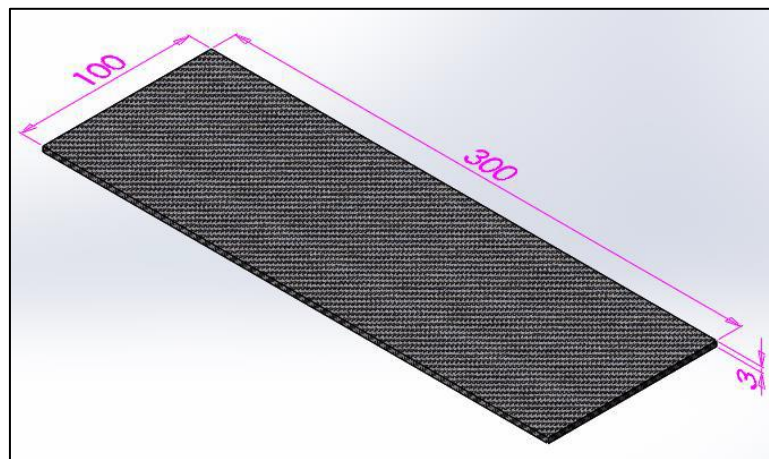


Figure 1. Illustration of CFRP used

Table 1. Physical Properties of Resin

RESIN		EPOLAM 2017 RESIN		
HARDENERS			EPOLAM 2017 HARDENER	EPOLAM 2018 HARDENER
Mix Ratio by Weight		100	30	30
Aspect		Liquid	Liquid	Light Amber
Viscosity at 25°C (MPa.s)	BROOKFIELD LVT	2,850	25	20
Density 25°C		Liquid	Liquid	Light Amber
Pot life at 25°C	ISO 1675:1985	1.17	0.96	0.96
Viscosity at 25°C	BROOKFIELD LVT	2MPa.s	550	450

Two flute solid uncoated carbide end mills (S2FE-080) was used to machine CFRP composite. The cutting tool has a diameter of 8.0 mm, a 20–24° relief angle, and a 30° helix angle. The actual photo and geometrical properties of the solid uncoated carbide cutting tool are shown in Figure 2 and listed in Table 2 respectively. The chemical composition and physical properties of the cutting tool are shown in Table 3 and Table 4.

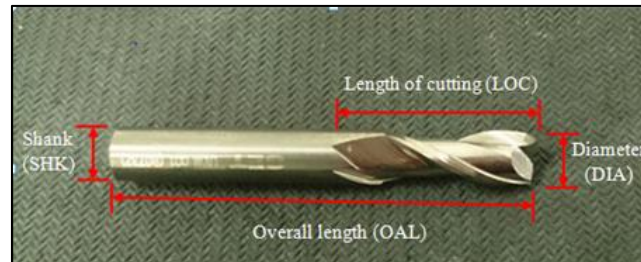


Figure 2 Carbide Cutting Tool

Table 2. Geometry of uncoated carbide cutting tool

DIA (mm)	SHK (mm)	OAL (mm)	LOC (mm)
8.0	8.0	60.0	20.0

Table 3. Chemical composition of uncoated carbide cutting tool

Element	Weight %
Tungsten Carbide, WC	88.4–90.0
Cobalt, Co	9.5–10.5
VC+Cr3C2	0.5–1.1

Table 4. Physical properties of uncoated carbide cutting tool

Density, g/cm ³	Hardness, HRA
14.35 ± 0.1	9.18 ± 0.5

A Computer Numerical Control (CNC) milling machine (DECKEL MAHO DMG DMU 35M) was used to machine the CFRP panel in the experiment. The tool wear of the cutting tool were measured by using a tool maker Nikon Microscope MM-40. During machining process, at every distance travelled of 200 mm, tool wear are recorded. The picture of the tool wear is captured for every distance travelled after machining process. The proper clamping method is the one of the important step to ensure that CFRP is not bending during machining process. The setup of the experiment is shown in Figure 3.

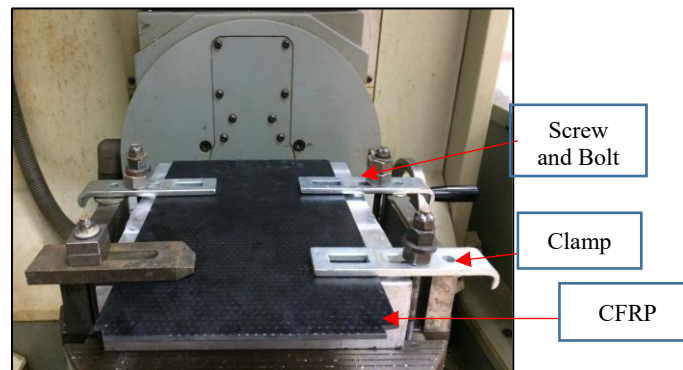


Figure 3. Machining Setup

RSM was utilized to conduct the experimental runs in this study. To reduce the number of runs, small Central Composite Design (CCD) was selected. Table 5 shows the five input variable levels which were used.

Table 5. Range of Cutting Parameters

Coded /Actual	Input Variable				
	Lowest $-\sqrt{2}$	Low -1	Centre 0	High 1	Higher $\sqrt{2}$
A:Cutting speed (rpm)	2361	3500	6250	9000	10139
B: Feed rate (mm/min)	190	225	200	250	260
C: Depth of cut (mm)	0.2	0.5	1.25	2.0	2.3

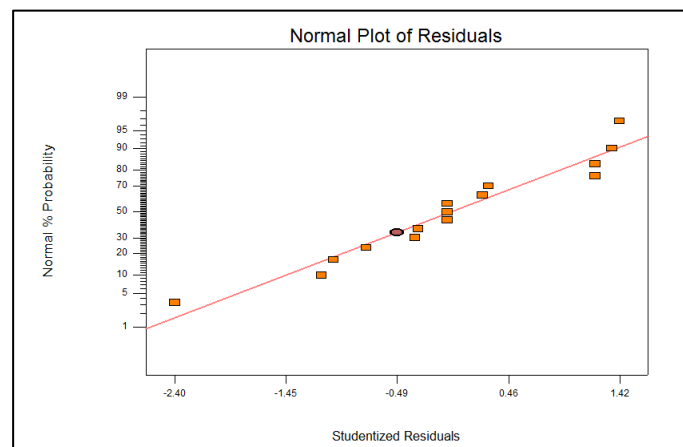
3. Results and Discussion

3.1. Effect of cutting speed, feed rate and depth of cut on tool wear

In industry, tool wear is the most important factor affecting the profitability and productivity of cutting process and cutting parameters such as cutting speed, feed rate and depth of cut, which have been identified as one of the factors that influence tool wear. Hence, it is important to find the suitable cutting parameters that can produce the optimize result (low tool wear) during machining. In this paper, analysis of tool wear was analyzed by using the analysis of variance (ANOVA). **Error! Reference source not found.** displays the ANOVA model to determine the tool wear. According to this model, the model F-value of 15.68 implies that the model is significant with value of “Prob > F” less than 0.05. There is only 0.0003% that a “Model F-Value” this large could exist due to noise. In this model, the significant model terms are main effect of cutting speed (A), feed rate (B) and depth of cut (C). The lowest “Prob>F” values indicates that feed rate (B) which is (0.0005) gives more influences in machining process compare to other main effects. Lack of Fit for this model is not significant with 15.89% relative to the pure error, so that, non-significant lack of fit model is good. The R^2 is 0.81 which is the value high and close to 1. The R^2 predicted is 0.59 which is reasonable agreement with the Adj. R^2 which is 0.75. A ration greater than 4 is desirable. Ratio in this model is 13.066 indicates an adequate signal. Figure 4 displays the normal probabilities plot of standardized residuals. It is shown that the plot is reasonable because of the point close to the straight line which presents that the error was normal distribute

Table 6. ANOVA Model for the Tool Wear

Response 1 Tool Wear						
ANOVA for Response Surface Linear Model						
Analysis of variance table [Partial sum of squares]						
Sources	Sum of	D	Mean	F	Prob>F	
Model	0.00050123	3	0.0001670	15.685	0.0003	significant
A	1.62855E-	1	1.62855E-	1.5289	0.242	
B	0.00024625	1	0.0002462	23.118	0.0005	
C	0.00023869	1	0.0002386	22.409	0.0006	
Residua	0.00011716	1	1.06517E-			
Lack of	9.79687E-	7	1.39955E-	2.9157	0.1589	not
Pure	0.0000192	4	0.0000048			
Cor	0.0006184	1				
$R^2 = 0.812$ $\text{Adj. } R^2 = 0.758$ $\text{Pred. } R^2 = 0.596$ $\text{Adeq. Precession} = 13.065$						

**Figure 4.** Normal probabilities of residuals for tool wear

Meanwhile Figure 5 shows the three-dimensional graph of the response surface for tool wear. It can be observed that as the cutting speed and feed rate increase, the value of tool wear is also increased which indicate that the tool life of the cutting tool is decreasing. According to Nor Khairusshima [8] at higher cutting speed, the cutting temperature is high, which worn out the cutting tool easily. Meanwhile, at higher feed rate, high rapid traverse of cutting tool is the primary reason of high tool wear during machining CFRP.

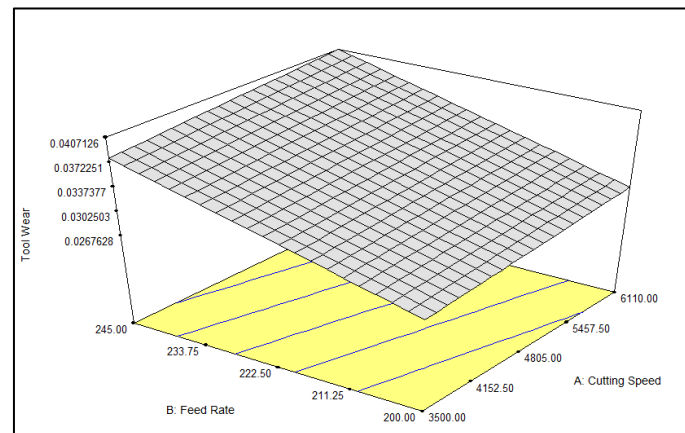


Figure 5 Three-dimensional graph of tool wear

Clearer view of tool wear can be seen in Figure 6. It can be seen that the shining area which has been identify by Nor Khairusshima [8] as abrasive wear is getting bigger as the feed rate increased. This Figure 6 is supporting the graph in Figure 5 which is developed by RSM.

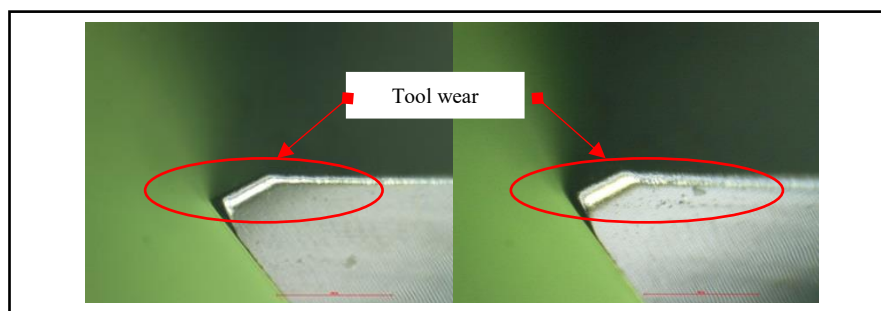


Figure 6. Growth of Tool Wear as Feed Rate Increased from (a) 191 mm/min and (b) 254 mm/min) as cutting speed and depth of cut are constant

The equation that describes linear surface Figure 5 is shown in equation 3.1

$$Tool\ wear = 0.039 + 1.427 \times 10^{-03} * A + 5.584 \times 10^{-03} B + 5.426 \times 10^{-03} * C \quad (3.1)$$

Where A is cutting speed, B is feed rate and C is depth of cut

3.2. Optimization

In machining operation, the determination of the most suitable and optimum cutting parameter is very important. By having optimization, the machining process can be conducted with guided cutting parameters that produce high quality results. There are 8 solutions of the optimization according to Design Expert software and it is tabulated in Table 7. According to the Table 7, highest desirability index obtained is 0.916. The best result (low tool wear in the range of cutting parameters) can be obtained at cutting speed of 3500.0 rev/min, feed rate 200 mm/min and depth cut 0.50 mm. These conditions yield optimum value of tool wear is 0.0267 mm respectively.

Table 7. Optimized solution of tool wear for machining CFRP

Optimized Cutting Parameter				Optimized	
No.	Cutting Speed	Feed Rate	Depth of Cut	Tool Wear (mm)	Desirability
1	3500	200	0.50	0.0267	0.916 (Selected)
2	3515	200	0.50	0.0267	0.915
3	3558	200	0.50	0.0268	0.913
4	3999	200	0.50	0.0273	0.891
5	4116	200	0.50	0.0274	0.883
6	3500	203	0.51	0.0275	0.876
7	4936	200	0.50	0.0283	0.841
8	5733	200	0.50	0.0292	0.799

4. Conclusion

The following conclusions are drawn from the results of this experiment:

1. Based to the ANOVA analysis, all the main cutting parameters (cutting speed, feed rate and depth of cut) are the significant factors to the tool wear.
2. Feed rate has been identified as the most pronounced factor which affect tool wear during milling CFRP compared to the cutting speed and depth of cut.
3. From the 3-D graph, it can be observed that as the cutting speed and feed rate increase, the value of tool wear is also increased which indicate that the tool life of the cutting tool is decreasing.
4. The shinning area on the cutting tool which has been identified as abrasive wear is getting bigger as the feed rate increase especially which indicate the tool wear is increased.
5. From the model developed, best optimization for tool wear (0.0267 mm) can be achieved by applying cutting speed 3510 rev/min, feed rate 200 mm/min and depth of cut 0.5 mm

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