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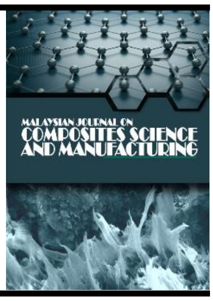

Analysis of Carbon Fiber-Reinforced Polymer Composites Delamination during Vibration Assisted Trimming using Historical Data Design

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ABSTRACT

Delamination is one of the main issues during the CFRP cutting process. This problem attracts researchers to investigate to meet the stringent quality need. This paper evaluates the influence of Rotary Ultrasonic Assisted Trimming (RUAT) when slotting carbon fiber reinforced plastic (CFRP). The study investigates rotation speed, vibration amplitude, and frequency particularly. The correlation effect of these parameters is to be evaluated by response surface methodology (RSM) to identify the minimum delamination. Seventeen trials were conducted with 38 plies of multi-directional CFRP panel. The trimming quality was determined by the minimum delamination damage of the slotting area analyzed by the ImageJ software. The best slotting quality can be achieved by applying spindle speed, amplitude, and frequency of 5305 rpm, 2.75 µm, and 26.79 kHz.

Keywords:
CFRP, vibration-assisted machining, trimming, optimization

1. Introduction

Carbon fiber-reinforced polymers (CFRPs) are prominently known as a lightweight material that possesses excellent mechanical properties. It is widely used in the aircraft, marine, and automotive industries. The layup process on mold is the popular approach to produce CFRP parts. This forming

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process sometimes requires a removal process. This material is considered difficult to machine due to the anisotropic and heterogeneous material characterization [1]. At present, the challenge of ultrasonic rotary machines for material hard and brittle is booming for advanced materials with high mechanical properties such as high hardness, high resistance to wear, low density, and resistance to abrasion at high temperatures [2]. However, the high cost of machining, ranging from 30-60% and even 90% of the production cost, affects the part manufacture. Composites are materials widely used in various industries, especially aerospace, due to their lightweight ratio and robust features [3]. Machining during panel fabrication of these materials cannot be avoided, even if produced to net shape components. It becomes more crucial when a design and shape require stringent dimension error and high-quality surface finish when the accuracy of dimensional tolerances and high material removal rate is needed.

The removal mechanism can be segregated into four types. It is based on the rake angle of the cutting tool, and CFRP builds orientation. Delamination, crushing-dominated damage, macro fracture, and out-of-plane workpiece damage are associated with these types during cutting processes [4–6]. Wang et al. [6] investigated a cutting force generated on the CFRP under elliptical ultrasonic vibration. The application of ultrasonic vibration has been proven to enhance surface quality and simultaneously decrease cutting forces. The cutting force can be improved as the ultrasonic amplitude reduces [7].

The panel of CFRP was made of impregnating the carbon fiber. This prepreg is made by reinforcing woven fabric with resin. The popular method is by laying up ply alternately. Therefore, there is a possibility of delamination or separation of CFRP composite laminates if an excessive unfavorable force is exerted during the cutting process [8-9]. Many research and development works were carried out on the effects of fiber in the type, volume fraction, design, and orientation. Fibers generally occupy 30% - 70% of the volume in the composite matrix [10]. Growth in demand until 2025 is presently anticipated due to a reduction of carbon fiber cost (USD 90/Kg) that would somewhat forecast still high at a rate of 12.5% even during this pandemic [11].

The aerospace industry or other industries that use carbon fiber reinforced plastics (CFRP) are often used in structural components to replace metal alloys. The purpose is to reduce the weight of the aircraft. These structural materials undergo a drilling process to be connected to other structures or components. The precision of the machine bore is critical to ensure the most efficient screw connection [12]. Henerichs et al. [13] reported on poor machinability of CFRP where the abrasiveness of this material led to a shorter tool life. Other factors are the high hardness of carbon fibers and the ease of melting them at high temperatures. Therefore, the application of ultrasonic vibration drilling has become a candidate for improvement as a cutting method for difficult machine materials.

The CFRP aircraft panels are generally made ready for shape by molding, vacuum bagging, and compression molding. However, a subsequent machining process such as water jet cutting, milling, trimming, or drilling is still required to ensure their bond with others. Therefore, dimensional tolerances and surface quality are required [14]. While machining carbon fiber composites, delamination at the machining edge is the main problem. Halim et al. [15] suggested this is due to the orientation of the multiple composite materials. It introduces the composite panels into anisotropy and inhomogeneity forms [12]. They claimed that ultrasound during the cutting process also causes problems such as poor tool performance, delamination, fiber removal, cracking, and staining [15].

Robert Voss et al. [16] demonstrated processing with variable fiber introduction, preparation parameters, and instrument geometry, focusing on workpiece surface quality, handle strengths, and tool wear. They conclude that high spindle speed and feed-rate create higher machining quality and cause lower powers than low spindle speed and feed-rate and a high bolster rate. It should be chosen to reduce the length of material contact for a specific application and enhance tool lifespan.

Boudelier et al. [17] suggest that high spindle speed with a small cutter increases productivity. They claimed the improvement in cutting mechanism cause of thermal effects could be controlled in CFRP material. Therefore, the cutting quality criteria can be achieved during the high spindle speed. Conversely, this finding varied with the study by Alazemi et al. [18], where high spindle speed generates heat that affects surface quality and tool performance. Wang et al. [19] suggested cutting with low speed, minimum feed-rate, and maximum radial depth of cut to achieve a high material removal rate without scarifying surface quality. Ning et al. [20] found that the increasing machining turn speed from 1000 to 5000 rpm reduced the cutting force in Rotary Ultrasonic Assisted Trimming (RUAT) and crushing.

In light of the above, this paper's main objective is to investigate slotting quality during the trimming of CFRP under ultrasonic conditions. The statistical analysis was done to evaluate the factors that influenced the result.

2. Methodology

The experiment setup to investigate the CFRP composite is shown in Figure 1. The workpiece is clamped on the special jig by using custom clamps. Each screw is located with 50 mm of distance to give sufficient clamping force and minimize the error due to the overhang effect. The vacuum hose was attached close to the cutting area to reduce pollution due to the trimming process.

Table 1 shows the cutting parameters factors for the historical data design selected for the Design of Experiment (DOE) using the Response Surface Methodology (RSM). A total of 17 experiment runs were generated under ultrasonic conditions. Three runs without ultrasonic were done as a benchmark trial. Each trial consists of several combinations of variable cutting parameters to obtain the response. The slotting area without any delamination of laminated prepreg and pull-out run matrix were selected as the responses.

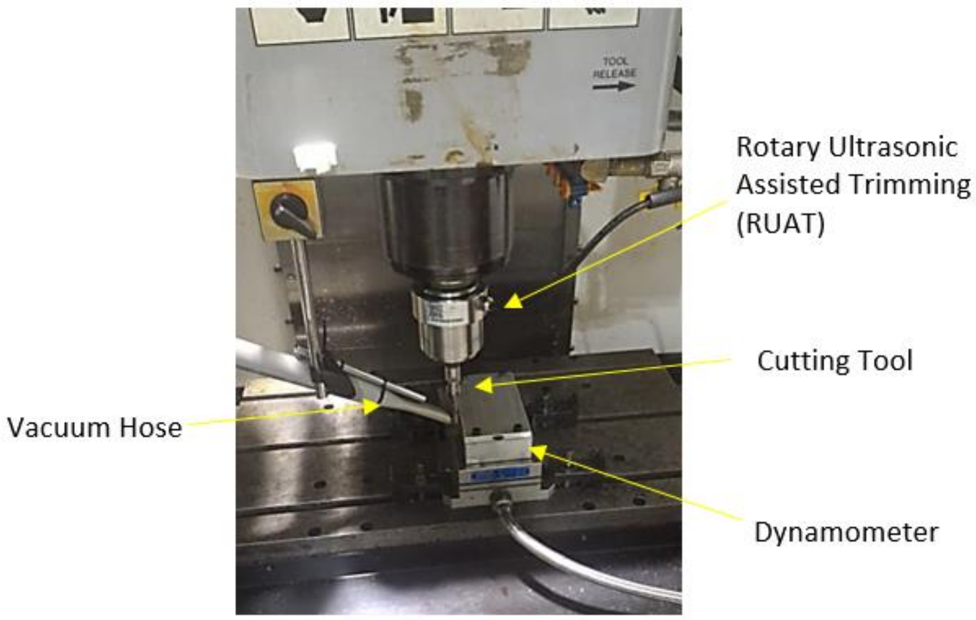


Fig. 1. Experiment setup

The feed rate was constant at 1000 mm/min, and the process parameters are tabulated in Table 1. The CFRP panels used woven-type fibers with a thickness of 10.31 mm. The rectangular panel shape dimensions were 150 mm x 275 mm, as illustrated in Figure 2. The specimen consists of 38 layers of prepreg in total. During layup, the CFRP prepreg orientation was stacked alternately between 45^{o} and 0^{o}/90^{o} to decrease the possibility of uncut fibers. Specific properties of the workpiece material are listed in Table 2.

Table 1
The Process parameters with their levels

Factors	Low	High
Speed (RPM)	1061	5305
Amplitude (µm)	1	3
Frequency (kHz)	20	27

Fig. 2. Carbon Fiber Reinforced Polymer (CFRP)

The machining started at the edge of the block with a straight-line strategy. The length of slotting was 15 mm. After the machining, image analysis using ImageJ software was performed to determine the area of slotting. The image of the software was calibrated to convert from pixel into mm unit. The experimental setup is shown in Figure 1. Meanwhile, Figure 3 shows the geometry overview of the router cutting tool applied in this study. The cutting tool of 6 mm diameter made of tungsten carbide material was used where the cutting edges are fabricated with various cutting geometry. Table 3 exhibits the detailed specification of the tool geometry for the mentioned cutting tool.

The quality of slotting of the composite material criterion can be defined by measuring the cutting area using image processing software. This software provides a better view of the damaged area, which helps find the affected area of the delamination. It will automatically outline the cutting area. The software will analyze and calculate the slotting threshold.

The damaged area (delamination) that appears inside the slotting affects the cutting area. Hence, delamination damage is the adverse effect of slotting quality. Figure 4 illustrates the measured area using ImageJ software. The measurement of the software automatically will be appeared in a millimeter unit.

Slotting areas with high delamination will be shown with a low slotting area (mm^2). That is because the damaged area has covered the slotting area. Theoretically, the slot area calculated should be 86.14 mm^2. However, considering the machining effect during the cutting process, the area was slightly bigger than the calculated area. The kerf width offset 0.1-0.2 mm gives the cutting area of 88.73 mm^2.

Table 2
Mechanical Properties of CFRP Material [20-21]

Mechanical Properties Of CFRP					
Property	Unit	Value	Property	Unit	Value
Density of CFRP	Kg/m^3	1550	Poisson's ratio of epoxy matrix	–	0.4
Hardness (Rockwell)	HRB	70–75	Young's modulus of epoxy matrix	GPa	4.5
Poisson's ratio (v12)	–	0.34	Fracture toughness of epoxy matrix (Energy/Gc)	J/m2	500
Poisson's ratio (v13)	–	0.34	Density of carbon fiber	kg/m^3	1800
Poisson's ratio (v23)	–	0.42	Poisson's ratio of carbon fiber	–	0.3
Longitudinal Young's modulus (E1)	GPa	136	Young's modulus of carbon fiber	GPa	230
Transverse Young's modulus (Et)	GPa	10.5	Fracture toughness of carbon (Energy/Gc)	J/m^2	2
In-plane hear modulus (G12)	GPa	3.76	Density of CFRP	kg/m^3	1550
Density of epoxy matrix	Kg/m^3	1200			

Table 3
Tool geometry specification

Diameter (mm)	Number of teeth	Number of flutes		Angle of helix (°)		Length (mm)
		Right	Left	Right	Left	
6	10	11	10	28	28	75

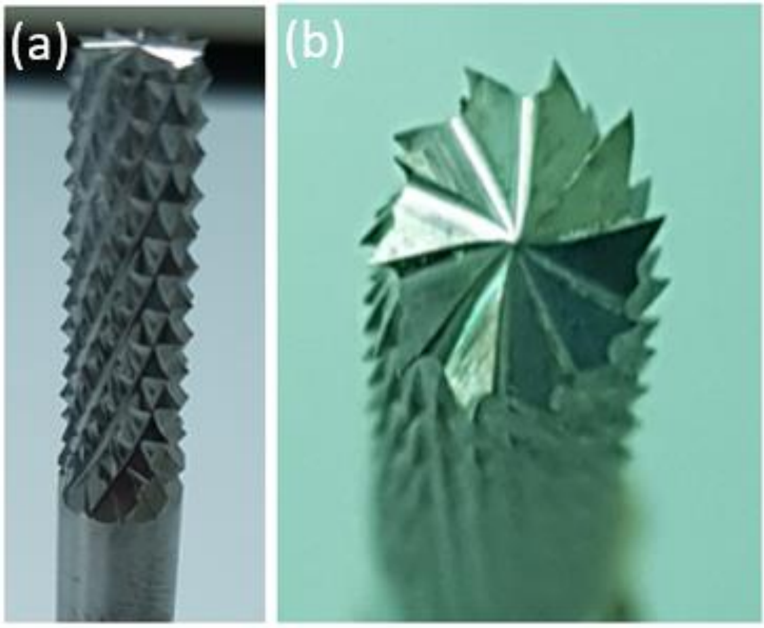


Fig. 3. Overview of the (a) 6.0 mm dia. router cutting tool with (b) diamond cross cut used in this study

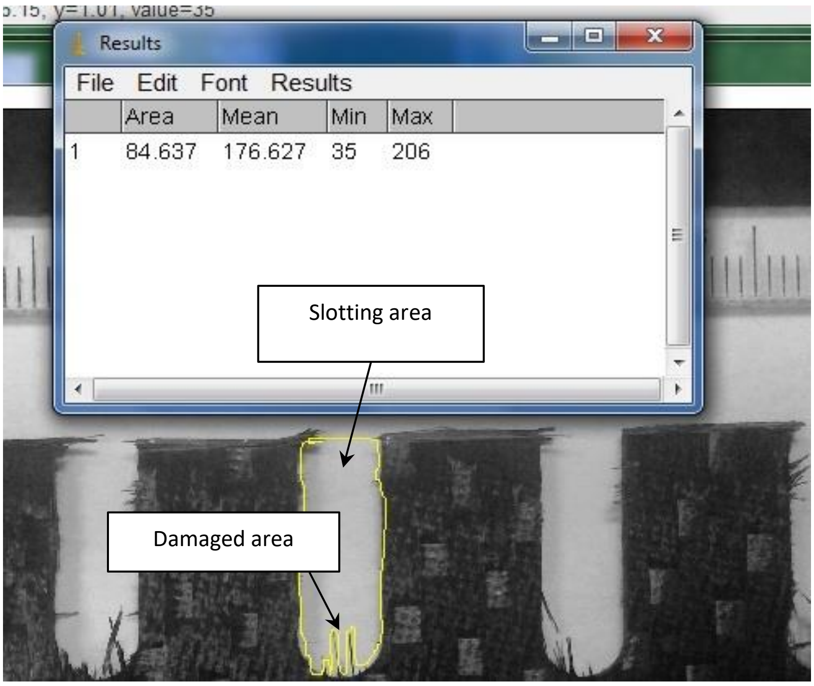


Fig. 4. Image Processing by ImageJ Software to evaluate the quality of slotting

3. Results

3.1 Experimental results

This section discusses the results obtained from the slotting profile measurement. Based on this experimental design setup, a total of 17 run with ultrasonic and 3 runs without ultrasonic for control parameters with different combinations of parameter features were recorded.

Figure 5 shows the comparison of trimming slots with and without ultrasonic application. Based on the enlarged image of the delamination damage, the damage type found was Type I. The delamination presents in the areas where the uncut fibers are broken and retain some distance inward from the cutting region. Type III delamination is also found where the partially attached fibers or cracks parallel to the feed direction.

However, type II damage is not found among the samples. Type II consists of the broken fibers that protrude outward from the cutting edge. During vibration-assisted trimming, it was found that the trim was free of delamination without leaving uncut fiber behind. This is because the additional micro-cutting by the ultrasonic oscillatory motion of the cutting tool improves material removal capability.

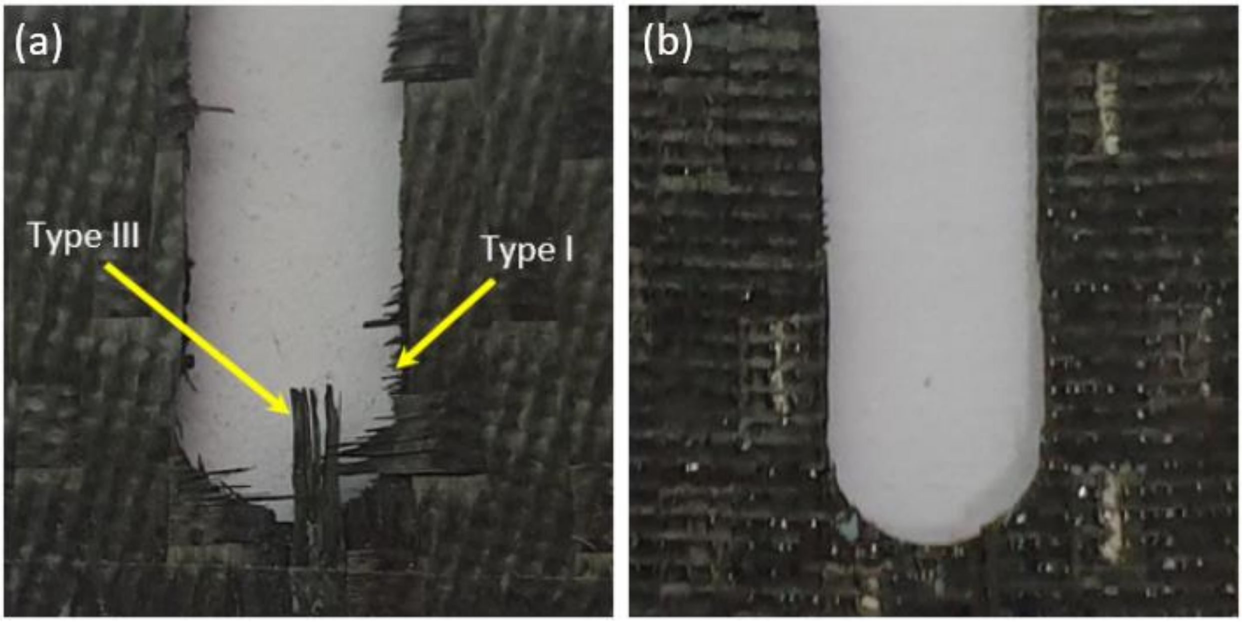
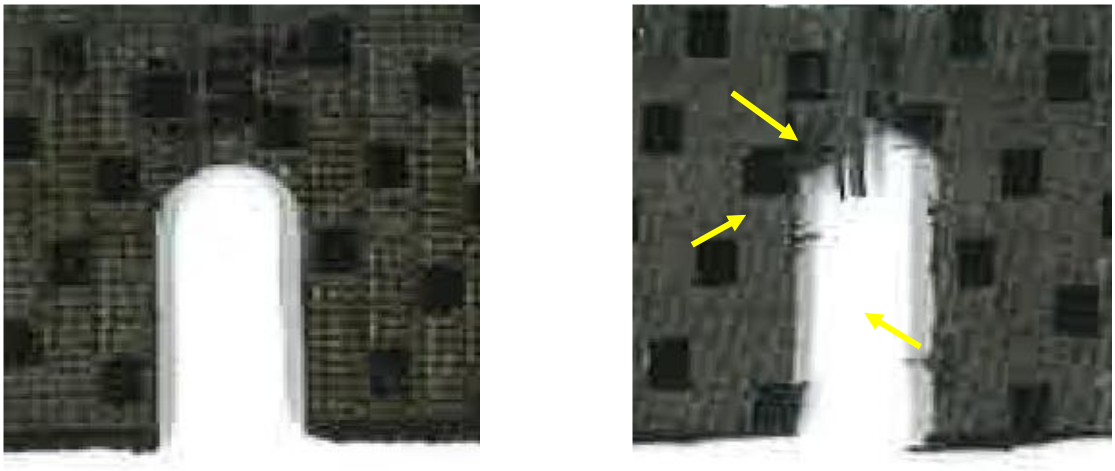


Fig. 5. Damage type during CFRP slotting (a) without ultrasonic and (b) with ultrasonic

Table 4 indicates the results of the slotting area observed by using ImageJ software, where the damaged area can be determined by the slotting area (mm^2). The maximum slotting area is run no. 8 with 88.695 mm^{2,} whereas the minimum is no. 14 with 47.93 mm^2.

Based on Figure 6, it can be seen the presence of uncut fibers on the cutting region in Figure 6 (b) effect on slotting area in Figure 6 (a). By observing all the slotting images, type III was frequent in the damage mode compared to type I. Type II damage was not found for the whole experiment images.



(a) (b)

Fig. 6. Slotting quality from the experiment (a) highest trimming quality with 88.695 mm^2 (b) lowest trimming quality with 47.93 mm^2

Table 4
Trimming parameter and response value

Run	Randomize	Factor 1 A: Spindle speed (rpm)	Factor 2 C: Amplitude (µm)	Factor 3 D: Frequency (kHz)	Response Slotting area, (mm^2)
1	4	3183	1	27	73.644
2	15	3183	1	20	58.289
3	20	5305	1	23.5	78.259
4	23	1061	1	23.5	48.795
5	2	3183	2	23.5	71.753
6	5	1061	2	27	53.66
7	8	3183	2	23.5	82.094
8	9	5305	2	27	**88.695**
9	19	1061	2	20	59.206
10	21	5305	2	20	58.611
11	24	3183	2	23.5	66.692
12	27	3183	2	23.5	81.673
13	28	3183	2	23.5	76.777
14	1	1061	3	23.5	**47.93**
15	3	5305	3	23.5	75.903
16	17	3183	3	27	83.391
17	26	3183	3	20	75.303

3.2 Statistical analysis

Table 5 shows the ANOVA for the trimming quality model. The model F-value of 5.16 implies this trimming quality linear model is significant. Lack of fit of F-value of 2.58 indicates the lack of fit model is not significant. There is only a 1.441 % chance that a “Model F-value” this large could occur due to noise. Values of “Prob> F” less than 0.05 indicate parameter terms are considered significant. In this case, the model comprising two factors, A (Speed) and C (Frequency), are significant model terms. Meanwhile, the term B (Amplitude) is not significant.

Delamination damage with different spindle speeds is shown in Figure 7. It can be seen that increasing trimming quality with a low delamination area can be achieved by increasing the spindle speed, which improves the cutting area. The poor quality with maximum delamination was observed during a low spindle speed of 1061 rpm rather than 5305 rpm. It is associated with the low ratio of engage cutting time in one rotation cycle over feeding time that some of the matrixes cannot be trimmed effectively. Higher rpm causes the diamond shape multi-tooth cutter of the tool periphery to cut faster. Cutting force reduction due to lower chip load suppresses delamination in RUAT. These results are agreed with the findings by Helmy et al. [21].

Table 5
The ANOVA for trimming quality

ANOVA for Response Surface Linear Model
Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	1412.21	3	470.74	5.16	0.0144	significant
A (Spindle speed)	1055.17	1	1055.17	11.57	0.0047	significant
B (Amplitude)	69.27	1	69.27	0.76	0.3993	Not significant
C (Frequency)	287.77	1	287.77	3.16	0.0991	significant
Residual	1185.52	13	91.19			
Lack of Fit	1011.12	9	112.35	2.58	0.1878	not significant
Pure Error	174.39	4	43.60			
Corr. Total	2597.73	16				

The effect of ultrasonic amplitude on delamination occurrence seems insignificant, as seen in Figure 8. However, the cutting quality shows the uptrend where delamination damage decreases as the amplitude increases. The parameter range of peak-to-peak distance is too close, which cannot be distinguished statistically (2 µm) [22]. The distance of 3 µm amplitude vertical cutting motion slightly over-performed 1 µm amplitude while cutting fiber filament of 7 µm diameter, minimizing uncut between plies more effectively.

Figure 9 shows the correlation effect of ultrasonic frequency on delamination damage. The trend is a similar pattern but more evident than a frequency amplitude factor. When the vibration frequency increases from 20 kHz to 27 kHz, delamination damage decreases by increasing slotting area (average) from 63 mm^2 to 75 mm^2. A good trimming quality can be obtained by setting the ultrasonic frequency at 20 kHz than 27 kHz. Additional ultrasonic oscillating of every single diamond tool tip trajectory during rotational motion improves the cutting mechanism.

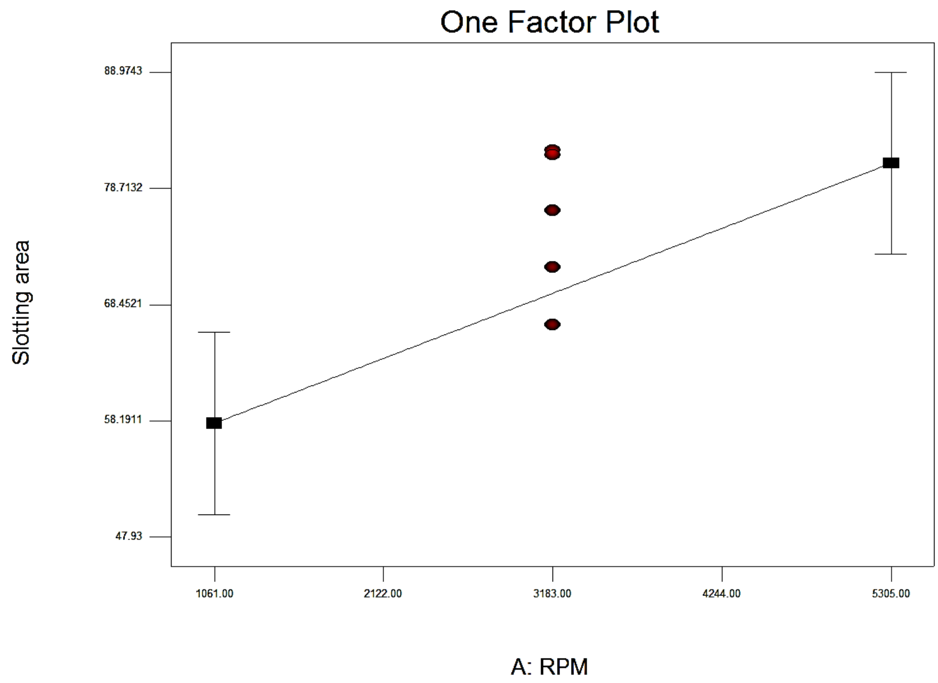


Fig. 7. The effect of spindle speed on slotting quality.

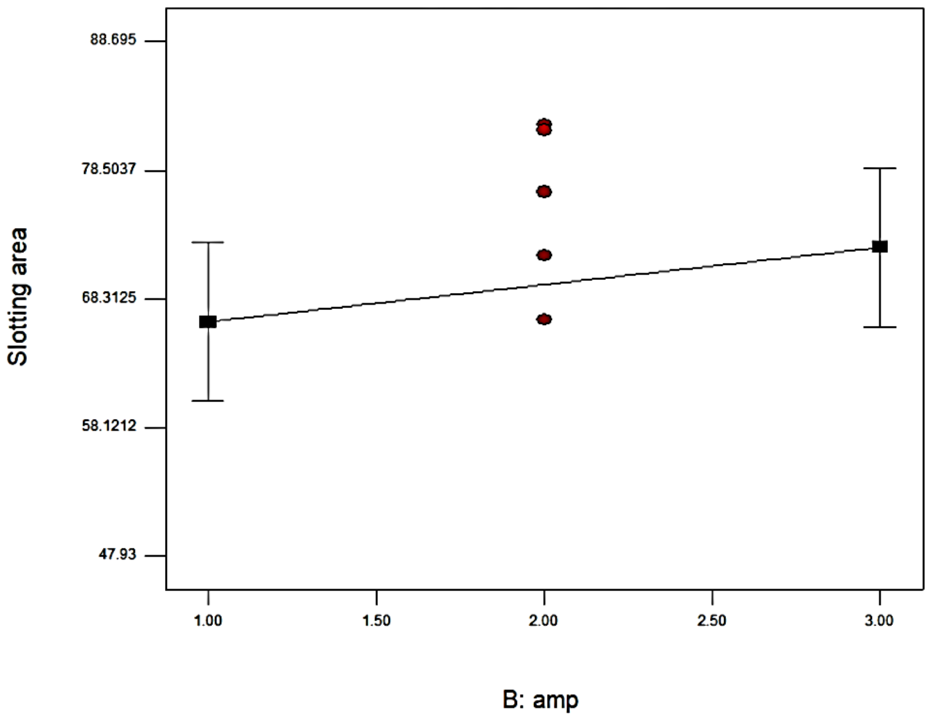


Fig. 8. Amplitude indicated a trivial effect on slotting quality

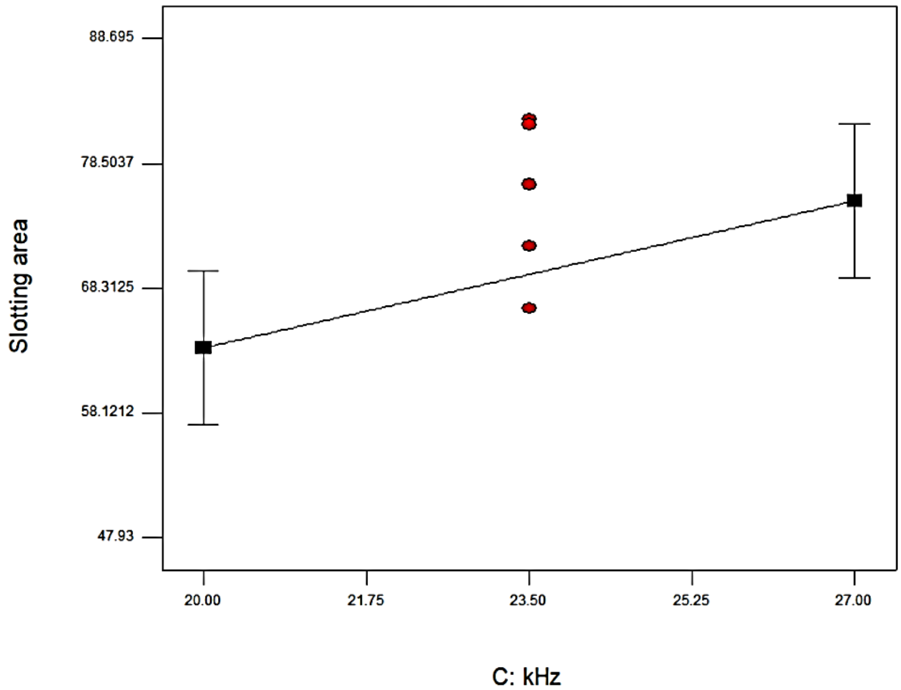


Fig. 9. Influent of ultrasonic frequency on slotting area

Based on the data set, the best combination suggested by statistical software to achieve the minimum delamination damage with 88.78 mm^2 slotting area will be the spindle speed of 5304 rpm, frequency amplitude of 2.75 µm, and ultrasonic frequency of 26.79 kHz.

4. Conclusions

This study evaluated the current investigation dealing with vibration-assisted CFRP trimming using a solid router milling cutting tool. It shows the application of RUAT application for multi-directional CFRP. Among the three parameters investigated, the spindle speed and ultrasonic frequency were statistically affected in trimming quality. In contrast, the vibration amplitude was found to be insignificant. High vibration amplitude and frequency produce less delamination at high spindle speed, as observed by ImageJ software. By adjusting to suitable trimming parameters, poor slotting quality can be suppressed to some extent.

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