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ORIGINAL ARTICLE

Experimental study and empirical analyses of abrasive waterjet machining for hybrid carbon/glass fiber-reinforced composites for improved surface quality

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Abstract

Poor surface quality is one of the critical defects after trimming of fiber-reinforced plastic (FRP) composites through both conventional and non-conventional machining processes. With the recent introduction of hybrid composites from different fiber reinforcements, this makes the trimming or cutting of them challenging. Therefore, an experimental study was attempted to elucidate the effect and relationship between the machining parameters in the abrasive waterjet cutting, namely abrasive flow rate, hydraulic pressure, and stand-off distance, and traverse rate on the surface roughness of the machined composites. An optimum setting of machining parameters and mathematical modeling equation were obtained by applying the response surface methodology for improving the surface quality. It is apparent that the abrasive flow rate and stand-off distance contributed the most in affecting the surface roughness of the hybrid FRP composites. The mathematical relationship, which is in the form of quadratic function, has been validated with confirmation test in order to optimize the surface roughness.

Keywords Abrasive water jet · Machining · Surface roughness · Design of Experiment (DOE) · Hybrid composites

1 Introduction

Fiber-reinforced polymer (FRP) composites have been well prominent in structural and non-load-bearing applications, notably for high-performance aerospace components as well as low-end consumer goods. The development of these composites has been deemed to be competitive due to several strict and demanding requirements on ductility and toughness as well as the weight. This eventually affects the performance of FRP composites for some specific structural applications. Over the years, fundamental studies on the mechanical performance of carbon or glass FRP composites have gained significant attention among research communities. Unfortunately, the setback of typical carbon fiber composites is that they possess a low ratio of compressive-to-tensile strength, which can hinder the performance of the composites [1]. On the other hand, the glass fiber composites are rather lacking in terms of high modulus-to-weight ratio. Therefore, hybrid composites that combine two or more fiber reinforcements have been introduced in order to complement what are lacking in one another, such as to achieve a balance strength and stiffness, to reduce cost, and to retain the superiority of the fibers [2, 3]. The existence of more than one type of fiber reinforcements leads to the hybrid composites, which possess properties that may not be realized or achieved in a single type of FRP composite or other metallic materials.

Fabrication of FRP composites usually involves combining, compacting, and processing the reinforcing and matrix materials. The steps to fabricate FRP composites are not only time consuming, but care intensive. This causes the costs due to processing to be highly substantial. Thus, FRP composites are typically and cautiously produced to near-net shapes via various processes such as wet hand lay-up, resin transfer molding, and autoclave manufacturing. Despite the near-net shape processing, final finishing processes that involve machining, trimming, and drilling operations are still essential to meet their functional and critical dimensional requirements.

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Edge trimming operation is often encountered as the first operation in the manufacturing plan to bring the FRP composites to their desired and final shape prior to assembly [4]. Therefore, the requirements of good quality and reliability of machined composites are of ultimate importance. The reason is that there will be an increase cost of discarding and repairing the damage piece or part of the FRP composites.

Previous fundamental understanding in conventional cutting of FRP composites is that it involves brittle fractures with little plastic deformation. Furthermore, an adequate level of edge sharpness on the cutting tool is vital to neatly shave the fiber reinforcement in the composites [5]. Standard cutting tool for machining metallic material is deemed unsuitable to trim or machine FRP composites. This was reported by Azmi et al. [6], in which the presence of fiber burrs or uncut fibers and severe delamination on the top side of milled surface when milling glass fiber reinforced polymer composites with four-fluted tungsten carbide end mill. Furthermore, Ahmad et al. conducted an experimental investigation to trim carbon fiber-reinforced polymer (CFRP) composite using router burr tools or also known as diamond-interlocking tools [5]. Although the authors suggested the best machining conditions for machining the CFRP using these tools, it was reported that surface roughness was high in the transverse direction as to that of the longitudinal direction. Also, no clear trends were found with regard to the surface roughness in the aforementioned direction. Due to this limitation, non-conventional approach such as abrasive waterjet machining has been attempted in past research studies.

Abrasive waterjet machining (AWJ) is a kind of non-conventional method that received a lot of attention from manufacturing industries to trim FRP composites. As a matter of fact, AWJ offers several advantages over that of conventional cutting processes, such as less thermal distortion, low tool wear, high machining versatility, and minimum stresses on the FRP composites [7, 8]. Despite these advantages, the major challenge concerning abrasive waterjet trimming of FRP composites is to achieve and maintain the required machining quality. Literature review disclosed that the machining process of the FRP composites through AWJ machining still contains delamination damage, poor surface roughness, and bad kerf geometry. Ramulu and Arola [9–11] were among the earliest to report the influence of pressure, grain size, stand-off distance, and traverse rate on the surface roughness and kerf taper of AWJ-machined graphite FRP composite. The results showed that the stand-off distance and grain size were the parameters that affect the surface finish of the composite materials. Later, Azmir and Ahsan investigated the effect and optimized the control and noise factors in AWJ cutting of multi-directional glass fiber composites (GFRP) [12, 13]. In their work, piecewise linear regression analysis was employed to establish an empirical model for the prediction of surface finish. As far as the cutting or fiber direction of the AWJ is concerned, Unde et al. [14] asserted that the fiber orientation and jet pressure affect the surface roughness of the trimmed CFRP composites. The 45° fiber orientation laminate gives superior results as to that of 60° and 90° orientations. The authors claimed that this was attributed to the greater resistance (due to large shear area) offered by the fibers at 45° orientation. In another recent study, Alberdi et al. reported the development of machinability index for various composite materials with different thicknesses machined by AWJ [8]. The effects of the AWJ parameters on the quality of cut (taper and surface roughness) were obtained in this study.

A recent investigation by Selvam et al. [15] showed the relative importance of cutting parameters such as water pressure, abrasive mass flow rate, traverse speed, and stand-off distance on surface roughness and kerf taper of thick hybrid carbon/glass FRP composites using response surface methodology (RSM). The authors have found that a rise in kinetic energy of the jet produces a higher impact of the abrasives, which leads to an effective cut of the composites and create better surface roughness on the work material. Although the work by Selvam et al. [15] is nearly similar to the one reported in our current study, the authors did not consider the position of roughness measurement on the machined slot wall as well as the number of readings taken. Their study also neglected the effect of penetration depth, in which the macro-mechanism depicting the AWJ process can occur to a certain depth of penetration of the abrasive water jet to produce striated surface. Therefore, it is essential to consider different positions of trimmed surface when measuring the R_a so that the roughness value would be more pertinent towards industrial applications. It has also been shown that the application of AWJ cutting is not only limited to synthetic fibers made from glass and carbon fibers. A recent research article has discussed an experimental study of AWJ cutting for green composite made from sundi wood saw dust. The authors claimed that very few attempts have been reported regarding the feasibility of using AWJ for machining of this green composite [16].

Based on the aforementioned discussion, it appears that the reported studies regarding machining of FRP composite through AWJ were limited to plain GFRP and CFRP. Database for effective cutting of hybrid composite made of carbon and glass fibers are still insufficient in the current literature despite the future potential applications of the composites. Hybrid composites of carbon and glass fibers have combinations of properties of that plain GFRP and CFRP. This makes the cutting of these composites extremely challenging. Therefore, research study on evaluation of optimized parameter setting for AWJ machining on hybrid FRP composite is highly essential. A number of parameters and factors of the AWJ process influence the quality of machined surface, such as abrasive type, hydraulic pressure, stand-off distance, abrasive flow rate, and traverse rate. In particular, a wider range of parameters was employed for traverse rate, abrasive flow rate, and hydraulic pressure as compared to the current literature, so that their effects on the surface roughness would be more pronounced. In this study, response surface methodology was used for the design of experimentation. This methodology was employed to obtain the optimal machining parameter on the AWJ machine for minimum surface roughness of the hybrid FRP composites.

2 Materials and methods

1. Machining conditions and surface roughness measurements

A 3.5-mm-thick carbon/glass hybrid FRP composite laminate, $[CW_2]_6$, composed of 12 layers of plain-woven glass fibers and 7 layers of plain-woven carbon fibers, was fabricated for machining tests in this present work, in which C and W are the weaved carbon fiber and glass fiber, respectively. The prepared specimens were then cut to dimensions of 100 mm × 50 mm × 3.5 mm. Detailed study on the mechanical properties of this hybrid composite can be found in previously reported article as in [17, 18]. It is to note here that the laminates were fabricated using vacuum-assisted resin transfer molding process. All cutting or trimming experiments were carried out on the Bystronic CNC waterjet cutting machine equipped with Bypump 50 APC ultra-high capacity pump at our industrial partner. The pump is designed to provide of 5300 Bar and driven by a dual-cylinder intensifier design. Prior to cutting operation, several parameters were set to be constant, as depicted in Table 1. This parameter setting was decided based on recommendations from our industrial partner. Figure 1 illustrates the overall setup on the CNC waterjet cutting machine.

Following the AWJ experimentations, the surface roughness of each trimmed hybrid FRP composite was measured using a contact surface roughness tester (Mitutoyo CS-3000 525-780E-1) at School of Manufacturing Engineering, UniMAP, as depicted in Fig. 2. Stylus with 2 μm tip radius and 90° tip angle was used for the measurements. In this measurement, the surface finishing parameter employed to indicate the surface quality was arithmetic mean roughness (R_a) as recommended in [4, 6]. Although other profilometry parameters are available, such as R_y, R_q, and R_z, it was generally acceptable that R_a can accurately describe the variation in the surface texture with depth of measurement for waterjet machining of FRP composites [10]. R_z and R_t may be better in capturing the surface severity as to that of R_a. However, due to the complicated fiber tow arrangement in the hybrid composite, such surface characterizations (R_y, R_q, and R_z) can be inadequate and misrepresentative of the true composite surface topography. In addition, since a total of 19 layers of 0.19 mm of plain-woven glass and carbon fabric were laid and compacted in composite laminates, it is difficult to judge the exact measurement position as well as the damage of every peak or valley. Therefore, the average surface roughness (R_a) was selected due to its extensive use and to prevent any subsequent characterization issues. Prior to the measurement, calibration was done using the reference specimen. The variation was within acceptable range of ± 0.05 μm. The setting of R_a measurement condition per region is showed in Table 2. All the measurements for the surface profiles were performed parallel to the feed direction. Based on the literature, surface waviness becomes serious with increasing depth of cut. Therefore, 45 mm length of specimen surface with 3.5 mm thickness is separated into three sections with a tolerance of approximately 7.5 mm from left and right (Fig. 3). Each section was measured by the distinction of 1 mm for each layer, which could produce nine measurements. The average of them was logged as the R_a. Tolerance is made by mean to prevent unnecessary noise.

Table 1 Details of the constant/fixed parameters for the AWJ process

Abrasive material/size	Garnet no. 80
Orifice material/diameter	Sapphire/0.28 mm
Mixing tube diameter/length	0.762 mm/69.85 mm
Nozzle material/diameter	Carbide/0.08 mm
Jet impact angle	90°

2. Design of experiment

Response surface methodology is an empirical modeling approach aimed at establishing the multiple linear regression model that determine the relationship between independent variables and response [18]. In this experimentation, the trimming process was studied according to the face-centered composite design (FCD) with a total of 30 experimental runs (16 factorial points—2^4, 8 axial points—2×4, and 6 center points) have been selected and carried out using Design Expert V8.0.6 software. Four principal machining parameters, which include abrasive flow rate, hydraulic pressure, stand-off distance, and traverse rate, have been employed to investigate the influence of these parameters on the surface roughness. These selected parameters have been varied in three different levels (− 1, 0, and 1) and listed in Table 3, in which − 1, 0, and 1 represent minimum, center, and maximum value. The selection of a range of parameters were based on a previously reported study of AWJ cutting parameters of CFRP and GFRP as well as industrial recommendations of our research partner. It is important to highlight that all machining procedures were executed using a single-pass cutting. The optimum values of the selected variables were obtained by analyzing the ANOVA, perturbation plot, and response surface contour

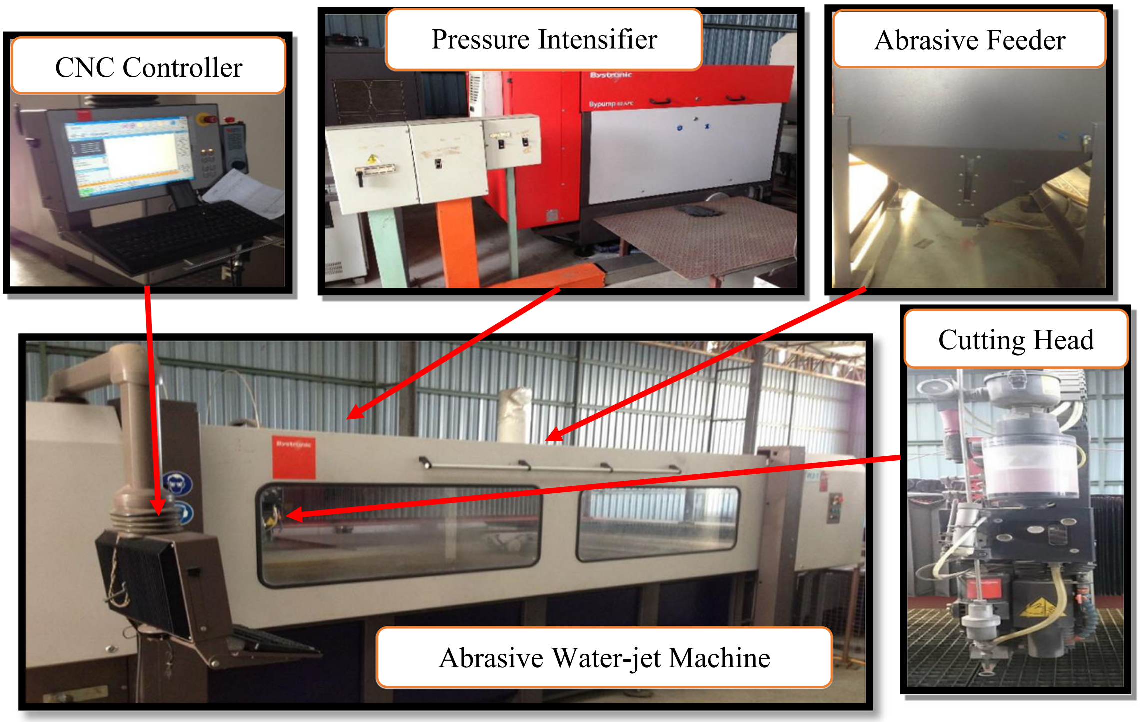


Fig. 1 Abrasive water jet machine

plots. The second-order polynomial model with interaction is normally utilized to predict the response for non-linear relationship using the RSM as given below:

$$Y=\beta_0+\beta_1(A)+\beta_2(B)+\beta_3(C)+\beta_4(D)+\beta_5(AB)+\beta_6(AC)+\beta_7(AD)+\beta_8(BC)+\beta_9(BD)+\beta_{10}(CD)+\beta_{11}(A^2)+\beta_{12}(B^2)+\beta_{13}(C^2)+\beta_{14}(D^2) \quad (1)$$

in which Y represents the value of surface roughness; β_0, β_1, ...β_{14} are the coefficients; and A, B, C, D is the abrasive flow rate, hydraulic pressure, stand-off distance, and traverse rate, respectively.

3 Results and discussion

1. Experimental results of surface roughness (R_a)

In this study, surface profilometry was used to measure arithmetic surface roughness, R_a at three different positions, which give a total of nine R_a measurements for every surface of machining specimens. The measurements were taken at the top, middle, and the bottom of the machined surface and compared as in scatter chart (Fig. 4). From that figure, it can be observed that the machined surface is smoother near the jet entrance (top) and gradually become rougher towards the jet exit (bottom) for most of the experimental runs. This is

Fig. 2 Surface roughness tester (Mitutoyo CS-3000 525-780E-1)

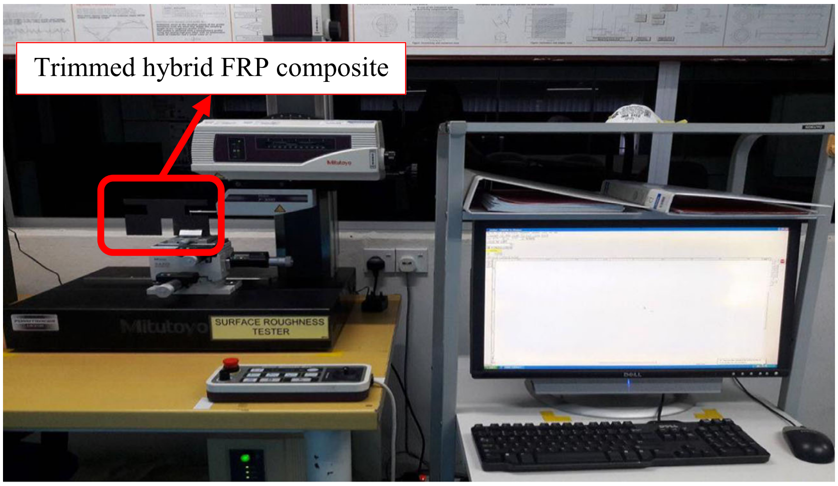


Table 2 Surface roughness measurement conditions in each region

Measurement condition	Value
Length of measurement	10 mm
Stylus tip diameter	2 μm
Stylus tip angle	90°
Pitch of measure	0.0005 mm
Speed of measuring	0.02 mm/s
Cut-off length	8 mm
Evaluation length	10 mm

Table 3 Process parameters and their levels used in the RSM

Process parameters	Symbol	Units	Factor level		
			− 1	0	1
Abrasive Flow Rate	A	g/min	120	360	600
Hydraulic pressure	B	MPa	200	260	320
Stand-off distance	C	mm	2	6	8
Traverse rate	D	mm/min	1000	1750	2500

because as the particles penetrated through, it loses the kinetic energy and hence, cutting ability deteriorates. These results support the finding of Arola and Ramulu [11] that mentioned kerf wall can be classified into three regions which is initial damage, smooth cutting, and rough cutting region. The data acquired for R_a in this project were taken with a tolerance of approximately 0.3 mm from the edge-machining surface. Hence, it was believed that the initial damage region was not part of the measurements for most of the experiment.

In addition, the error bar in Fig. 4 denotes the range of standard deviation for the roughness measurements. It can be observed that the experimental results for Exp. 4, Exp. 13, and Exp. 18 have a sizeable variation, which was ± 4.50, ± 2.96, and ± 2.55 μm, respectively. This implies that the average surface roughness values (from top and bottom) for these sets of experiments were spread far from the mean. All of the three experiments were carried out under lowest abrasive flow rate and fastest traverse rate. These conditions can significantly reduce the kinetic energy of the abrasive waterjet stream. Adding to that, the cutting efficiency of abrasive may be decreased due to the loss of pressure in the abrasive water stream after discharging from the focusing nozzle.

Besides that, the graph also indicates that the best attainable surface roughness is when the parameters were set according to the parameters in Exp. 16 (at $A_1B_11_{-1}D_{-1}$), in which the value of R_a is 5.7 μm, in which A_1, B_1, C_{-1}, and D_{-1} are $A_1 =$ 600 g/min, $B_1 = 320$ MPa, $C_{-1} = 2$ mm and $D_{-1} = 1000$ mm/min, respectively. Conversely, the highest R_a value of 18.4 μm can be observed in Exp. 13 (at $A_{-1}B_{-1}1_1D_1$), where A_{-1}, B_{-1}, C_1, and D_1 are $A_{-1} = 120$ g/min, $B_{-1} = 200$ MPa, $C_3 = 8$ mm, and $D_3 = 2500$ mm/min, respectively. The average roughness values were also found to be more or less similar in the top, middle, and bottom zones, which is evidenced in Table 4. It is worthwhile to mention that R_a was measured along the fiber and waterjet-penetrated directions as recommended by Azmi et al. when machining with conventional milling process [19].

Usually, FRP composites will have striated marks after machining by abrasive waterjet. Figure 5 shows the SEM images for Exp. 16 (at $A_1B_1C_{-1}D_{-1}$) and Exp. 13 (at $A_{-1}B_{-1}C_1D_1$). The striated marks can be apparently observed on Exp. 13 image, which resulted in a very high R_a value compared to that of Exp. 16. The rougher surface is always followed with a high degree of undesirable defects such as fiber pull out, debonding on the fiber-matrix interface, void, and delamination which can be easily distinguished in Fig. 6 of Exp. 13. Additionally, close-up view of Fig. 7a for Exp. 16 shows a relatively smooth cutting surface finish with marginal fiber-matrix debonding and delamination on the carbon fiber tows after the trimming process. However, observation on Fig. 7b

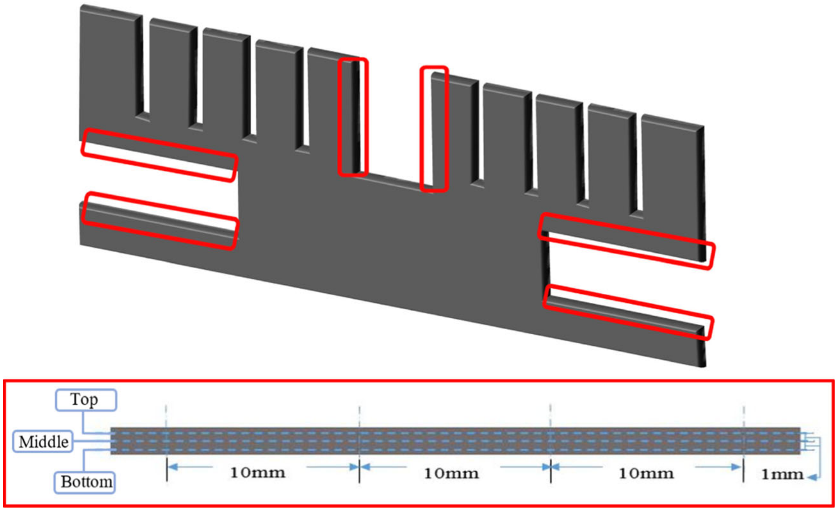


Fig. 3 Surface region for measuring surface roughness

* The surface layers section which highlighted in red region

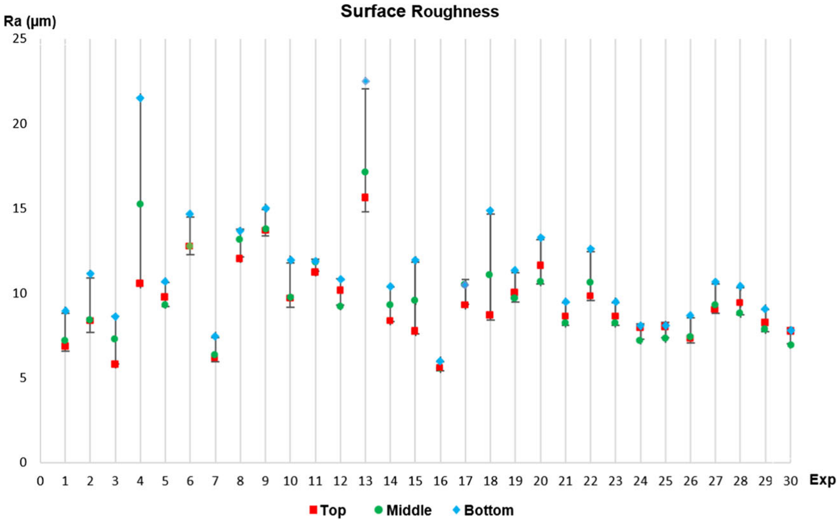


Fig. 4 Comparison of the measured surface roughness (top, middle, and bottom)

Table 4 R_a values of each experimental parameters

Std	Run	Factors				Response			
		A	B	C	D	Top	Medium	Bottom	Ra (µm)
12	1	600	3200	2	2500	6.896	7.201	8.959	7.685 (±0.91)
8	2	600	3200	8	1000	8.338	8.438	11.140	9.305 (±1.30)
3	3	120	3200	2	1000	5.809	7.256	8.616	7.227 (±1.15)
9	4	120	2000	2	2500	10.578	15.222	21.558	15.796 (±4.50)
18	5	360	2600	5	1750	9.768	9.313	10.699	9.927 (±0.58)
5	6	120	2000	8	1000	12.763	12.771	14.678	13.404 (±0.90)
2	7	600	2000	2	1000	6.235	6.316	7.499	6.683 (±0.58)
14	8	600	2000	8	2500	12.044	13.178	13.667	12.963 (±0.68)
15	9	120	3200	8	2500	13.683	13.739	15.052	14.161 (±0.63)
17	10	360	2600	5	1750	9.699	9.735	11.977	10.470 (±1.07)
16	11	600	3200	8	2500	11.229	11.828	11.865	11.641 (±0.29)
19	12	360	2600	5	1750	10.161	9.240	10.800	10.067 (±0.64)
13	13	120	2000	8	2500	15.661	17.136	22.541	18.446 (±2.96)
10	14	600	2000	2	2500	8.355	9.260	10.408	9.341 (±0.84)
1	15	120	2000	2	1000	7.715	9.525	11.935	9.725 (±1.73)
4	16	600	3200	2	1000	5.532	5.593	6.031	5.699 (±0.22)
6	17	600	2000	8	1000	9.258	10.484	10.512	10.085 (±0.58)
11	18	120	3200	2	2500	8.703	11.075	14.894	11.558 (±2.55)
20	19	360	2600	5	1750	10.022	9.703	11.352	10.361 (±0.71)
7	20	120	3200	8	1000	11.637	10.668	13.290	11.865 (±1.08)
26	21	360	2600	8	1750	8.624	8.190	9.489	10.319 (±0.54)
21	22	120	2600	5	1750	9.842	10.591	12.641	11.025 (±1.18)
29	23	360	2600	5	1750	8.624	8.190	9.489	8.768 (±0.54)
22	24	600	2600	5	1750	7.947	7.230	8.066	7.748 (±0.37)
27	25	360	2600	5	1000	8.042	7.316	8.111	7.823 (±0.36)
25	26	360	2600	2	1750	7.338	7.432	8.666	7.812 (±0.61)
23	27	360	2000	5	1750	9.045	9.288	10.656	9.663 (±0.71)
28	28	360	2600	5	2500	9.408	8.794	10.405	9.536 (±0.66)
30	29	360	2600	5	1750	8.260	7.848	9.097	8.402 (±0.52)
24	30	360	3200	5	1750	7.733	6.959	7.828	7.507 (±0.39)

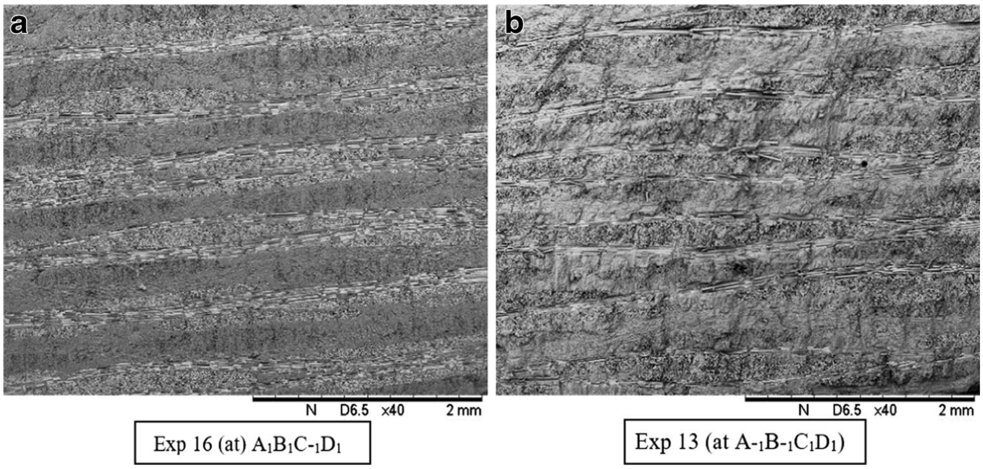


Fig. 5 Cross-section surface topologies for **a** Exp 16 at highest abrasive flow rate [600 g/min—A$_1$], highest hydraulic pressure [320 MPa—B$_1$], lowest stand-off distance [2 mm—C$_{-1}$], and slowest traverse rate [1000 mm/min—D$_{-1}$] and **b** Exp 13 at lowest abrasive flow rate [120 g/min—A$_{-1}$], lowest hydraulic pressure [200 MPa—B$_{-1}$], highest stand-off distance [8 mm—C$_1$], and fastest traverse rate [2500 mm/min—D$_1$]

reveals a coarse surface finish with uncut glass fiber, severity fiber-matrix debonding, striated marks, or uneven surface for Exp. 13.

Generally, in AWJ of hybrid FRP composites, the material is removed by erosion action of highly abrasive water jet that penetrates on the workpiece surface [20]. Based on the observation from Fig. 7, carbon plies can represent brittle failure of material whereas glass fiber represents ductile failure. When sharp-edge abrasive particle are in contact with the carbon plies, a relatively neat finishing was produced. This is due to the brittle failure of the carbon fibers. Erosion force produced by abrasive water stream can efficiently generate bending fractures on the carbon fiber tows and washes out the matrix. In machining of glass plies, the material removal process can be classified into high (Exp. 16) and low (Exp. 13) erosion cutting force. Under high erosion force, high momentum of

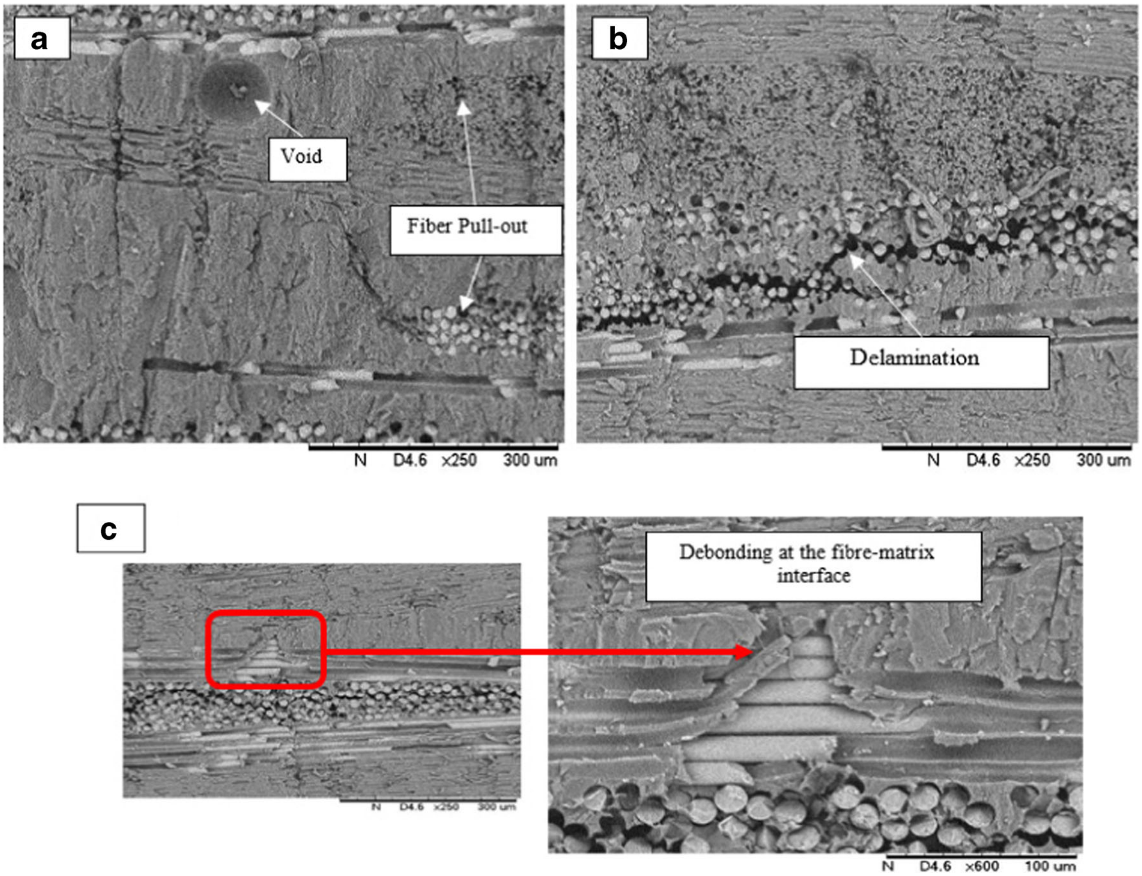
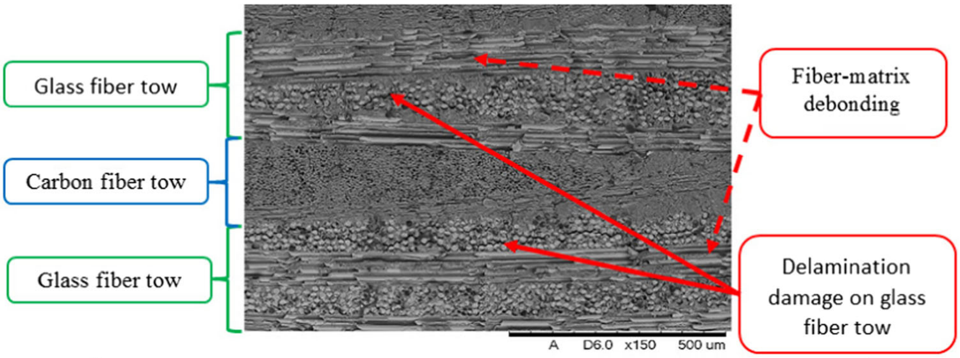
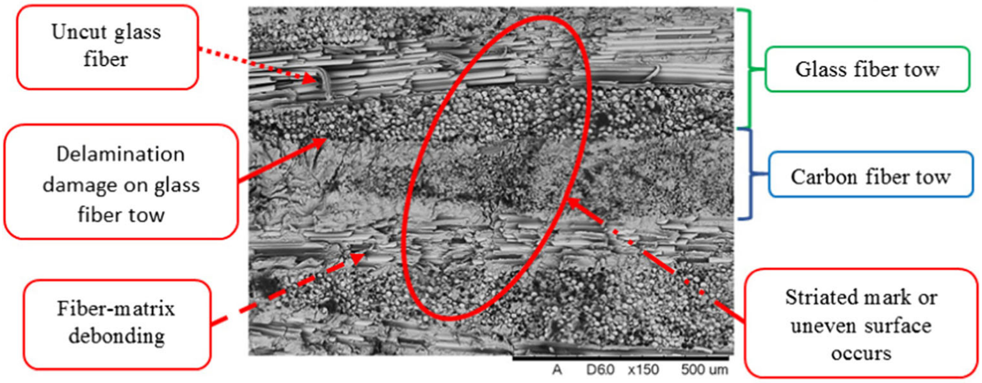


Fig. 6 SEM images of AWJM surface topologies form Exp 13 at lowest abrasive flow rate (120 g/min—A$_{-1}$), lowest hydraulic pressure (200 MPa—B$_{-1}$), higher stand-off distance (8 mm—C$_1$), and faster traverse rate (2500 mm/min—D$_1$)

Fig. 7 Close-up SEM image of cross-section surface for **a** Exp.16 and **b** Exp. 13



a Exp 16 at higher abrasive flow rate (600 g/min), higher hydraulic pressure (320 MPa), lower stand-off distance (2 mm), and slowest traverse rate (1000 mm/min)



b Exp 13 at lowest abrasive flow rate (120 g/min), lowest hydraulic pressure (200 MPa), higher stand-off distance (8 mm), and faster traverse rate (2500 mm/min)

sharp abrasives onto the workpiece has enhanced the erosion process and glass fiber was removed through plastic deformation, which polished the unwanted glass fiber in the weft direction. Thus, fiber-matrix debonding in the weft direction of glass fiber is more apparent. On the other hand, glass fiber deforms plastically beyond their yield point and tends to produce uncut fibers with severe fiber-matrix debonding when machining under low erosion force. Similar point of view is well agreed with the conclusion made by [14]. Apart from the machined surface itself, the striated mark of the machined surface quality is another issue with AWJ [21]. This striated mark is apparent due to the different process parameters, which generate curved lines and rougher surface on the kerf surface. It is essential to note that the effect of fiber orientation laminates also one of the factors that affect the surface roughness of trimmed hybrid composite.

In this study, the hybrid FRP composite was trimmed in the turbulent flow through abrasive waterjet machining. Thus, the highly pressurize water jet diffused to the surrounding atmospheric air after leaving the focusing nozzle and then, diverged progressively. Anirban [22] and Qun Luo et al. [23] have carried out numerical simulation to analyze the water jet characteristics in terms of velocity, pressure, and water formation. The structure of high-pressurize water jet in the air can be divided into three distinct zones namely potential core, main, and diffused droplet zone. A wedge-shaped water jet core that is near to the nozzle exit carries velocity equals to the nozzle exit velocity, and it is believed that it can provide an adequate cutting quality. Therefore, the larger the standard deviation or variation of average surface roughness represents the area of which the abrasive water stream is no longer on the potential core zone as the sliding erosion rate in the downstream area gets severe [24]. This combination of parameter setting provides an extremely unacceptable roughness values which is not recommended for industrial practice.

Table 5 indicates the surface roughness range of different types of FRP composite while machining by conventional and AWJ machining process. Haddad et al. [4] studied the influence of the trimming processes through the abrasive diamond cutter, standard cutting tool, and AJEM technology. The result shows the abrasive diamond cutter generates better surface roughness compared with standard cutting tool. It is believed that the abrasive wear occurs when the CFRP composite is loaded against the abrasive grains, which wear away the less resistant material [25]. On the other hand, it can be observed from Table 5 that the surface roughness of the machined hybrid carbon/glass FRP composite material was slightly higher while comparing with the previous study. This is due to that the traverse rate of the nozzle used in this study is much higher as compared to that of Selvam et al. [15] and P. Shanmughasundaram [26]. With the higher traverse rate of

Table 5 Comparative table of R_a values obtained by different machining methods

Ref.	Year	Material	Machining method	Parameter Feed/traverse rate (mm/min)	Roughness range (μm)
[3]	2014	Carbon FRP composite	Standard cutting tool	125–500	6.4–19.8
			Abrasive diamond cutter	125–500	8.9 ± 2
[21]	2009	Aramid FRP composite	AWJM	30–180	6–12
[22]	2016	Carbon/glass FRP composite	AWJM	100–200	2.7–6.3
Current study		Carbon/glass FRP composite	AWJM	1000–2500	5.7–18.4

nozzle travelling across the penetrating area causing less number of abrasive particle to overlap machining motion which is attributed to the difficulty in attaining clean cuts [27]. Despite all this, high productivity with acceptable surface roughness is the main concern in composite manufacturing industry nowadays. Also, the results in this study have contributed approximately five times the traverse rate with a comparable and acceptable surface roughness quality, which can enhance the cutting productivity. Traverse speed is directly proportional to the productivity and should be set as high as possible unless the surface roughness or kerf ratio is the primary concern.

2. Statistical analyses on the effect of experimental parameters on surface roughness

The R_a values were averaged out for each of the experimental parameters and tabulated as in Table 4. These results were inputted into the Design Expert software for subsequent statistical analyses. The data were fitted to various models (linear, two-factorial, quadratic and cubic) to find the suitable empirical model. The subsequent ANOVA outputs of the aforementioned models showed that R_a was most suitably described with quadratic polynomial models. The terms that are not significant were reduced automatically by selecting backward elimination procedure with an alpha value of 0.05.

As shown in Table 6, ANOVA evaluation implied that the experiments could be well described by these models since the model F-value of 98.82 indicates that the model is significant. There is only a 0.01% of chance that a "model F-value" could occur due to noise. Furthermore, the ANOVA output for surface roughness corresponds to 95% confidence level. The result indicates that all parameters are significant in producing a smooth trimming surface in which the F-value of the factors is higher than the table value ($F_{0.05,\,1,\,29} = 4.18$). Hence, the data from the ANOVA table concludes that the process factors A, B, C, D, AB, AD, BD, and A^2 have significant influence on the surface roughness, in which A, B, C, and D are abrasive flow rate, hydraulic pressure, stand-off distance, and traverse rate, respectively.Furthermore, the coefficients of determination (R^2) of the empirical model were found to be 0.98. The value for R^2 is close to 1, which bespeaks that the model can represent the experiment very well. Besides that, "Adeq Precision" is a measure of the range in predicted response relative to its associated error. In other words, it represents the signal-to-noise ratio. A ratio greater than 4 is desirable. Adeq Precision was found to be 41.69 (more than 4), which indicates an adequate signal. On the other hand, the "lack of fit F-value" of 0.19 shows not significant relative to the pure error. This is good since it suggests that the model is fit enough. The modeling equation for final response equation of surface roughness (R_a) is illustrated in Eq. 2. From the equation, it implies that some interactions occur when the surface roughness response is different depending on the parameter settings of two factors. It is consistent with the fact that the second-order effect of abrasive flow rate is the most significant among the other order effects:

$$\begin{aligned} R_a = {} & 9.73 - 1.78\,A - 1.08\,B + 1.70\,C + 1.63\,D \\ & + 0.49\,AB - 0.49\,AD - 0.36\,BD + 0.73\,A^2 \end{aligned} \tag{2}$$

3. Effect of AWJM process parameters on surface roughness

From literature review, surface roughness values due to the AWJM can be minimized by manipulating the process parameter, which includes abrasive flow rate, hydraulic pressure, stand-off distance as well as traverse rate. The effects of each of these parameters are studied and illustrated in Fig. 8 while keeping the other parameters as constant. The general trend of AWJM parameters presented from this figure was that the surface roughness improves with an increment in the abrasive flow rate and hydraulic pressure. In contrast, it gets rougher with the growth of stand-off distance and traverse rate.

(a) Effect of abrasive flow rate on surface roughness

In the case of abrasive flow rate, Fig. 8a shows that the increase in abrasive flow rate will lead to a rapid decline in the surface roughness. This is due to the fact that a rise in the number of abrasive tends to increase the number of impacts per unit area under a certain pressure. The collision of the

Table 6 ANOVA analysis for R_a (after backward elimination with P value < 0.05)

Source	Sum of squares	DF	Mean square	F-value	*p* Value Prob > F	
Block	25.6870	2	12.8435			
Model	190.3907	8	23.7988	98.8249	< 0.0001	Significant
A-Abrasive flow rate	57.0950	1	57.0950	237.0877	< 0.0001	
B-Hydraulic pressure	21.0353	1	21.0353	87.3494	< 0.0001	
C-Stand-off distance	52.2322	1	52.2322	216.8946	< 0.0001	
D-Traverse rate	47.7305	1	47.7305	198.2013	< 0.0001	
AB	3.8195	1	3.8195	15.8603	0.0008	
AD	3.8820	1	3.8820	16.1199	0.0007	
BD	2.0311	1	2.0311	8.4341	0.0091	
A^2	2.5652	1	2.5652	10.6520	0.0041	
Residual	4.5755	19	0.2408			
Lack of fit	4.3176	16	0.2699	3.1390	0.1882	Not significant
Pure error	0.2579	3	0.0860			
Cor total	220.6533	29				
Std. Dev.	0.4907	R-squared		0.9765		
Mean	10.1670	Adj R-square		0.9667		
C.V. %	4.8267	Pred R-squared		0.9315		
PRESS	13.3464	Adeq precision		41.6882		

particles can levitate along the surface of the composite material. Thus, the increase in the amount of abrasive can easily enhance the penetration of jet to cut through the laminate and creates a smoother cutting surface.

Additionally, abrasive flow rate also determines the number of impacting abrasive particles and total kinetic energy available. Therefore, the increase in abrasive flow rate should strengthen the cutting ability of the water jet. Despite this, numerous

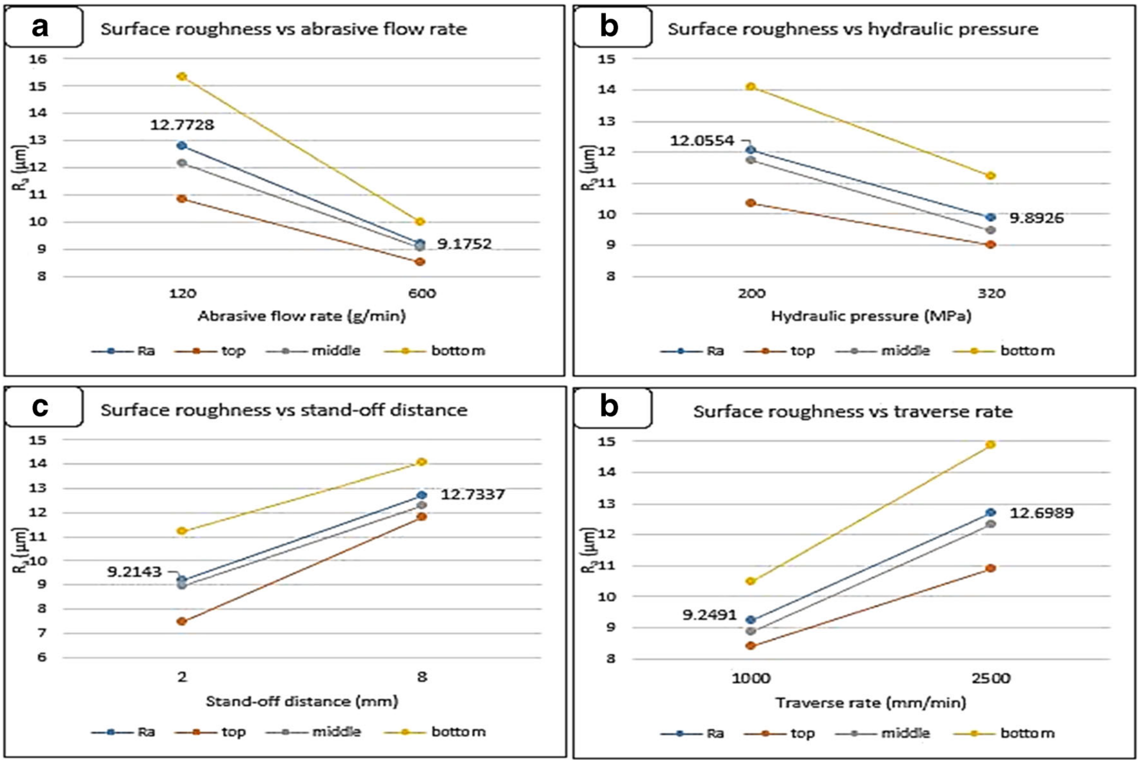


Fig. 8 Main effect plots of surface roughness on the hybrid FRP composites

researchers reported that with the rise in abrasive flow rate, it generates a higher inter-particular collision among them and thus lose kinetic energy [13, 28]. Apparently, surface finishes near the jet entrance are smoother and progressively increase towards the jet exit. Another essential point, which needs to be mentioned, is that the abrasive can get trapped in the mixing chamber once a large amount of abrasive flows at the same time.

(b) Effect of hydraulic pressure on surface roughness

The influence of water pressure on the surface roughness is shown in Fig. 8b. The surface roughness reduced by 22% when the water pressure increased from 200 to 320 MPa. It was attributed to the increases in the momentum of the abrasive particles with high-pressure water, and this enhances their ability for material removal. Abrasive particles gain more cutting energy to grind the machined surface and make it smoother. Similar observation was made by several researchers [26, 29], which reported that increasing in water pressure improves the surface quality for other different materials.

(c) Effect of stand-off distance on surface roughness

Figure 8c shows that the surface roughness of hybrid FRP composites appears to have an increment trend with an increase in the distance between the nozzle and workpiece. Higher stand-off distance allows the jet to diverge and reduce the kinetic energy before impingement through the workpiece. This phenomenon is illustrated in Fig. 9. The higher stand-off distance increases vulnerability to external retardation from the surrounding atmosphere air before the jet penetrated through the composite [30]. Concurrently, it lowers the kinetic energy of abrasive to grind the machining surface. Similar observation was also made by Unde et al. [14], in which the authors reported that when the stand-off distance increases, the surface roughness getting serious considerably in machining of CFRP composites.

(d) Effect of traverse rate on surface roughness

The relationship between the surface roughness and traverse rate is shown in Fig. 8d. Surface roughness increases from 9.2 to 12.7 μm when traverse speed was increased from 1000 to 2500 mm/min. This can be concluded that by increasing the traverse rate of the focusing nozzle, it causes less amount of abrasive particle available to overlap with machining a unit area, hence resulting to a rougher surface [14, 29].

(e) Effect of interaction variables on surface roughness

Response surface and contour plots that represent the effect of two variables and their interaction on R_a when other variables are set at the middle level are depicted in Fig. 10. It is evident that from Fig. 10a, better surface finish can be achieved at highest abrasive flow rate combined with a highest hydraulic pressure. Figure 10b shows that the better surface finish can be gained at lowest traverse speed combined with the highest abrasive flow rate. Furthermore, Fig. 10c reveals that the better surface finish can be acquired at highest hydraulic pressure combined with the lowest traverse rate. In summary, better surface finish can be achieved by increasing kinetics energy of waterjet stream when impinging to the composite. It is vital to mention that the current results have well agreed with the conclusion made by Azmir et al. [31].

(f) Effect of all variables on surface roughness

From the perturbation plot in Fig. 11, the effect of all factors on the surface roughness after machining is represented. The abrasive flow rate shows a significant influence on the response, followed by stand-off distance, traverse rate, and hydraulic pressure. In the case of abrasive flow rate, it indicates that the increase in the abrasive flow rate will result in more collision of the particles, which levitated among the surface of the composite material. Thus, high quantity of abrasive particles can readily enhance the penetration of jet to cut through the laminate and create a smoother cutting surface. Meanwhile, lower stand-off distance allows the jet to impinge the composite material in a shorter period of time before it expands as it exits the workpiece. A smoother surface finish can be produced due to smaller jet diameter as cutting is initiated and also due to increase kinetic energy generated from inter-collision between abrasive particles in that short period [14, 26].

On the other hand, under slower traverse speed or feed rate, the abrasive particles have more time to impinge the composite materials as well as increase the overlap machining action. In this study, a relatively high traverse speed has been selected to minimize the machining costs and to increase the production rate, which eventually yields satisfactory quality of the composite material. It is also clear that increasing the hydraulic pressure will accelerate the momentum of abrasive particles and enhances their capability for material removal [13]. The result of this paper has shown that the influence of hydraulic pressure is trivial compared to the other parameters, which is in contrast with the study reported by Azmir et al. when cutting GFRP composites [13].

4. Optimization of surface roughness response for hybrid FRP composites

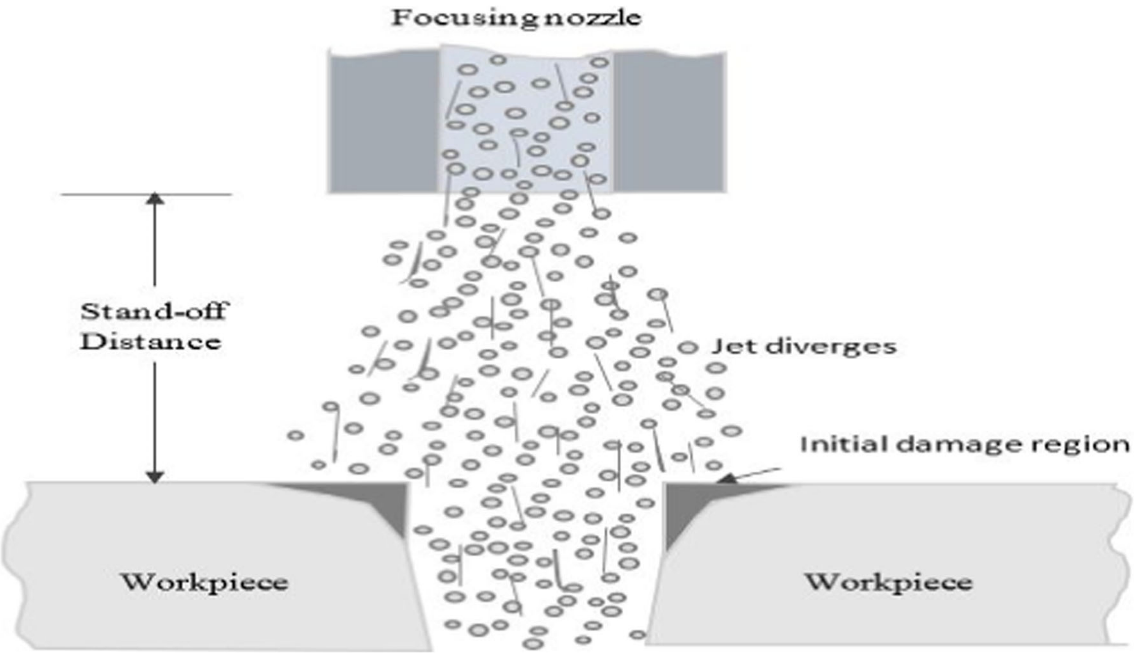
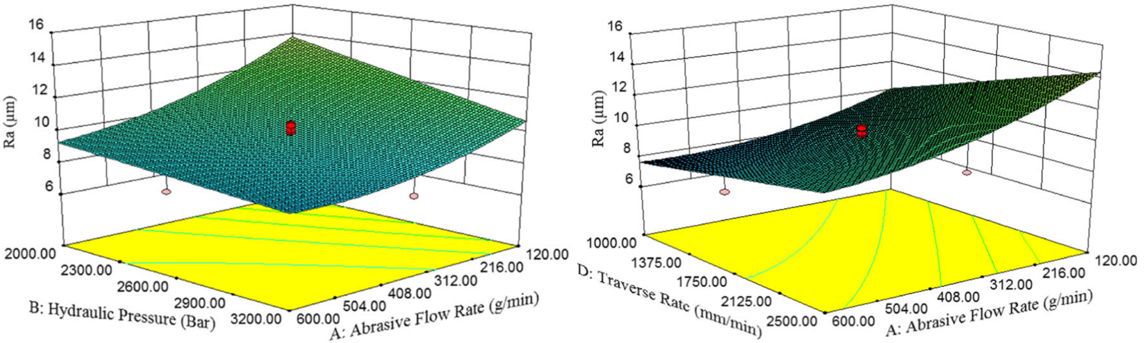


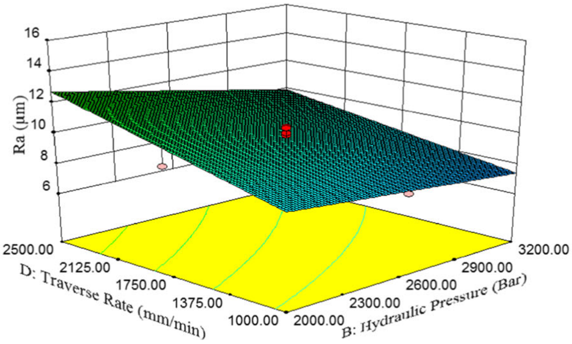
Fig. 9 Jet diverges after exiting from the abrasive water jet-focusing nozzle

In the present study, desirability function optimization of the RSM has been employed for single-response optimization. The use of response surface optimization helps to find the optimal values of cutting parameters in order to minimize or improve the surface roughness during the AWJ cutting process. Under the specified machining conditions, abrasive flow



a Effect of abrasive flow rate and hydraulic pressure on Ra

b Effect of abrasive flow rate and traverse



c Effect of hydraulic pressure and traverse rate on Ra

Fig. 10 Response surface and contour plots that represent the effect of two variables and their interactions on R_a when other variables are at middle level. **a** Abrasive flow rate and hydraulic pressure. **b** Abrasive flow rate and traverse rate. **c** Hydraulic pressure and traverse rate

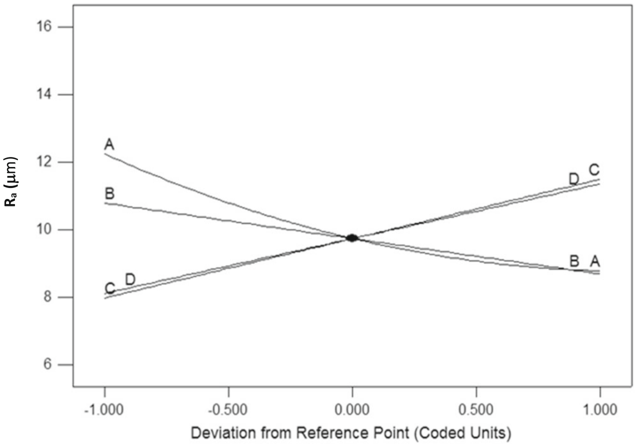


Fig. 11 Perturbation plot showing the effects of all factors on R_a

rate = 600 g/min, hydraulic pressure = 3200 Bar, stand-off distance = 2 mm, and traverse rate = 1000 mm/min are considered as the optimum drill process parameters which predicted a minimum R_a value of 5.603 μm. A validation experiment has been conducted according to the aforementioned parameter settings. The R_a indicated a value of 5.137 μm, which agrees with the prediction at approximately 92%.

4 Conclusion

This paper presents the effect of various parameters, namely abrasive flow rate, hydraulic pressure, stand-off distance, and traverse rate, in AWJ process of carbon/glass hybrid FRP composites. ANOVA, response surface, and contour plots were used to draw the following conclusions. Abrasive flow rate has a more significant influence on the response (surface roughness), followed by stand-off distance, traverse rate, and hydraulic pressure. The results obtained were attributed to the kinetic energy generated from the inter-collision between the abrasive particles on the machined workpiece that produce the machined surface. A quadratic response surface model for the aforesaid performance characteristics has been developed from the experimental data, and this developed model can be effectively used to predict these performance responses on the machining of hybrid FRP composites. Abrasive flow rate = 600 g/min, hydraulic pressure = 3200 Bar, stand-off distance = 2 mm, and traverse rate = 1000 mm/min are considered as the optimum AWJ process parameters which predicted a minimum R_a value.

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