

Performance Analysis of Cutting Glass Fibre Epoxy Reinforced Composites Using an Abrasive Water Jet Machining Process

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Abstract

Abrasive Waterjet Machining (AWJM) is a versatile cutting process that involves directing a high-velocity stream of water mixed with abrasive particles to remove material and create holes and cavities in solid materials. In this study, the impact of abrasive waterjet machining (AWJM) parameters, including traverse speed, stand-off distance, and abrasive flow rate, while maintaining a constant pressure, on glass fibre epoxy composites were investigated. The glass fibre composites were made up of 50% glass fibre, 47% epoxy, and 3% graphite by weight. The aim of this study is to assist industries and individuals in selecting optimal AWJM parameters to achieve desired kerf width and surface roughness while meeting specified standards. Central Composite Design (CCD) integrated with Responsive Surface Methodology (RSM) was employed to determine the experimental parameters. Analysis of Variance (ANOVA) and regression models were established to predict kerf width and surface roughness based on primary and interaction effects of process parameters. Kerf width was measured using a Vernier caliper, while surface roughness was assessed using a surf test machine (SV-600). The study reveals that surface roughness is influenced by machining parameters such as stand-off distance, traverse speed, and abrasive flow rate, along with the interaction between stand-off distance and traverse speed. In contrast, kerf width is predominantly influenced by stand-off distance and traverse speed. Additionally, a morphological analysis of the samples was conducted using Optical Microscopy and Scanning Electron Microscopy (SEM) to examine surface microstructures.

1. Introduction

Glass fibre reinforced composites (GFRC) are a type of composite material that consists of a matrix polymer resin reinforced with glass fibres. GFRC are esteemed for their high strength-to-weight ratio and stiffness, making them well-suited for applications where lightweight materials with robust structural integrity are essential [1]. These properties collectively make GFRC a favorable choice in industries such as aerospace, automotive, marine, electrical and electronics, construction, and sports equipment [1]. Application of fabricated GFRC depends on the ease of machining as it needs to be processed through secondary operations to transform the material into finished part or to assemble the parts. The common secondary machining operations include cutting, drilling, turning, and milling. One of the problems associated with GFRC is the machinability [2]. The traditional machining

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of GFRC poses various challenges such as delamination, lower precision, cracks, higher surface roughness make it difficult to choose appropriate machining technique to obtain better results [3]. These complications have underscored the need for identifying sustainable and effective machining techniques specifically tailored for composite materials like GFRC. Abrasive Waterjet Machining (AWJM) emerges as a prominent non-traditional machining method, exhibiting superior efficiency in working with GFRC compared to other unconventional techniques. The primary advantage of AWJM lies in its capacity to preserve the integrity of the workpiece, as it generates no heat and produces no chips during the process [4]. AWJM works with a high-speed stream by a mixture of water and rough abrasive particles on the surface that materials need to get removed [5]. Water jet cutting, which is aimed at cutting, originates from high-pressure fluid systems, and was designed for hard materials. To enhance the efficiency by removing material faster, it employs a high-speed combination of abrasive particles and water. Importantly, this process is environmentally friendly and does not alter material properties due to the absence of thermal effects [4].

The machining parameters of AWJM play the biggest role such as the speed of the water jet and stand-off distance to ensure the cutting process works. This variation is an important parameter in design and installation specifications for geometric evaluation. Surface roughness assesses the flaws and deviations on a machined surface after using an abrasive water jet. The quality of surface roughness and the width of the cut (kerf) in the composite material are influenced by chosen machining parameters [5]. However, challenges arise when selecting these parameters because they can lead to either excessively rough or overly smooth surfaces and varying kerf widths, depending on specific requirements. Studies by Anu Kuttan et al. [6] highlighted the importance of machining parameters in AWJM. They observed that the machining of epoxy glass fiber composites had received limited attention in the past, with only a few parameters considered, such as cutting speed and abrasive flow rate. Tripathi et al. [7] focused on cutting glass fibre-reinforced polymer materials, using only cutting speed and abrasive flow rate as parameters for their experiments. Doreswamy et al. [8] found that kerf width increased with pressure and stand-off distance but decreased with feed rate for graphite/glass/epoxy composites. They also noted that smooth surface roughness was achieved with high pressure and abrasive flow rate, which is significant for material removal rate. Increased traverse speed and abrasive flow rate were observed by Arola et al. [9] to produce the highest material removal rate and smoothest surface finish on various materials, including thin fibre metal laminate-titanium/graphite.

Hreha et al. [10] discovered that higher abrasive flow rates reduced vibrational fluctuations and raised metal material peaks in their study. A study on FRP hybrid composites indicated that stand-off distance and traverse rate lowered the kerf ratio and delamination damage [11]. Rajesh et al. [12] identified water jet pressure as the most influential factor in reducing surface roughness and kerf ratio for titanium metal-interleaved basalt-flax fibre laminates. Pressure, abrasive flow rate, and traverse speed were ranked in the order of importance for material surface roughness [13]. The influence of abrasive water jet machining parameters on various responses is critical, as highlighted by Patel et al. [14]. The process is highly dependent on parameters like operating pressure, traverse speed, abrasive flow rate, stand-off distance, and nozzle diameter. These factors impact output characteristics such as surface roughness and kerf width, both of which are vital in assessing the quality of cutting. Kerf width, as noted by Arola et al. [9], is an important consideration as it affects cut accuracy and dimensional integrity. Surface roughness, on the other hand, evaluates defects and deviations on the machined surface following the use of an abrasive water jet. The quality of these two parameters depends on the input parameters: traverse speed, stand-off distance, abrasive flow rate, and operating pressure.

The choice of machining parameters plays a role in achieving desired surface quality and kerf width in abrasive water jet machining. Several studies have explored these parameters and their impact on the cutting process, highlighting their significance in optimizing the machining of materials like glass fibre reinforced epoxy composites. Therefore, the relationship between the surface roughness and kerf width of glass fibre epoxy composites and the machining parameters used are investigated in this study. Other than that, the study aimed to determine the best possible cutting conditions to achieve the necessary quality. The Central Composite Design (CCD) analysis has been used to analyze this study using the Design Expert software to determine the ideal cutting condition. This study mainly emphasizes the optimization of the cutting process using an abrasive water jet and examines how machining parameters affect the kerf width and surface roughness of the material.

2. Materials and Methods

2.1 Materials

The material employed in this study possesses a thickness of 4 mm and consists of a glass fiber epoxy composite. The composition of this composite material comprises 3% graphite, 47% epoxy, and 50% glass fiber by weight.

2.2 Experimental Setup of AJWM

The Abrasive Water Jet Machining (AWJM) parameter combines several effects which are fixed parameters and variable parameters. The fixed parameter considers the operating pressure. Whereas, the variable parameter considers the stand-off distance between specimen and nozzle, operating traverse speed, and abrasive flow rate. The experiments are carried out on the abrasive water jet machine FLOW Mach 100 series. The machine has a maximum traverse speed of up to 10 meters per minute, and its linear straightness precision can reach up to 0.13 millimetres per minute of deviation. The abrasive that is utilized is a silica-based abrasive that has a mesh size of 80. A height of 20 mm and a length of 20 mm have been entered into the machine's computer as the dimensions for the design.

2.3 Kerf Width, Surface Roughness Measurement and Microstructure Analysis

Kerf width measurement is the specimen of the section that has been cut out which is the inner length that has been measured by using a vernier caliper. Then, the outer length of the square cut is measured and subtracted from the inner length value. Lastly, the value will be divided by two to get the kerf width value for one run. Then, the specimen was tested for surface roughness which was measured with a Surftest SV-600, which measures the degree of roughness of a target's surface. The surfaces that have been cut by an abrasive water jet have been placed under the machine's stylus. The stylus will measure the roughness along 5mm of each side of the specimen. Then, the average value is taken and recorded. An examination of the surface condition of the specimen is carried out to establish whether any instances of delamination, fiber pull-out, or abrasive embedment. A morphological analysis was carried out on the surface that had been machined using non-optimized parameters. Lastly, to figure out the defect of the specimen surface, microstructure analysis has been done. The analysis was carried out using SU3500 Scanning Electron Microscope (SEM), to examine the microstructure of the surface after the cutting process.

2.4 Optimization AWJM Parameters Through Central Composite Design

In this study, Response Surface Methodology (RSM) through Central Composite Design (CCD) has been used to analyze the performance of the parameters of AWJM on machining glass fiber epoxy composite gathered by developing its analysis. Following a review of the relevant literature, the machining parameters and levels for the trials were selected, and then the capabilities of the machine were taken into consideration. The machining parameters and levels that were decided upon are detailed in Table 1. Variable parameters which are traverse speed, stand-off distance, and abrasive flow rate used to determine the optimum machining parameter via using Analysis of Variances (ANOVA) in Design Expert Software (Version 22.0.6, 2023, Stat-Ease, Inc. MN USA). Utilizing optimization tool in the Design Expert software allowed for the formation of the experiment's plan, which was then implemented. The Central Composite Design (CCD) resulted in the formation of a combination of eighteen experimental run, all of which had good predictions in the centre of the design.

Table 1 Abrasive water jet machining parameters

Machining parameters / Levels	1	2	3
Stand-off Distance (mm)	5	10	15
Traverse Speed (mm/min)	2000	2500	3000
Abrasive Flowrate (Kg/min)	0.28583	0.30171	0.31759
Operating Pressure	Constant = 379 MPa		

The experimentation data has been analyzed for a better understanding of the result. ANOVA data analysis provides information on which parameters have the greatest influence on both kerf width and surface roughness. This software's numerical optimization solution yielded the ideal machining parameters. Then, the numerical optimization results for optimum parameters can be achieved.

3. Results and Discussion

A total of eighteen experiments have been conducted making use of an abrasive water jet machine with different sets of parameter combinations with consideration of several outcome factors, including surface roughness and kerf width. The analysis was carried out through the Design of Experiment (DOE), and the results are currently being analyzed with the assistance of the Analysis of Variance (ANOVA), as well as the mathematical regression model. The results of the experiment are detailed in Table 2. The average surface roughness ranged from a minimum of 2.24 μm to a maximum of μm while for kerf width, the values obtained ranged between 0.98 mm and 1.35 mm.

Table 2 Results of surface roughness and kerf width

Run	Stand-off Distance (mm)	Traverse Speed (mm/min)	Abrasive Flowrate (kg/min)	Surface roughness (um)	Kerf Width (mm)
1	5	3000	0.31759	2.73	0.99
2	10	2500	0.30171	2.84	1.15
3	15	2000	0.28583	2.96	1.35
4	10	2500	0.31759	2.69	1.15
5	15	3000	0.31759	2.87	1.30
6	15	3000	0.28583	2.98	1.29
7	10	2000	0.30171	2.67	1.20
8	5	2500	0.30171	2.58	1.00
9	5	2000	0.31759	2.24	1.00
10	10	2500	0.30171	2.75	1.15
11	10	2500	0.30171	2.82	1.15
12	15	2000	0.31759	2.76	1.35
13	5	2000	0.28583	2.54	0.99
14	5	3000	0.28583	2.95	0.98
15	10	3000	0.30171	2.85	1.12
16	10	2500	0.28583	2.90	1.14
17	10	2500	0.30171	2.79	1.15
18	15	2500	0.30171	2.96	1.35

Table 3 ANOVA and fit statistics of surface roughness analysis

Sources	Sum of Squares	df	Mean Square	F-value	P-value	
Model	0.5666	9	0.0630	43.67	< 0.0001	significant
A-Stand-off distance	0.2220	1	0.2220	153.97	< 0.0001	
B-Traverse Speed	0.1464	1	0.1464	101.54	< 0.0001	
C-Abrasive flow rate	0.1082	1	0.1082	75.01	< 0.0001	
AB	0.0741	1	0.0741	51.40	< 0.0001	
AC	0.0055	1	0.0055	3.82	0.0863	
BC	0.0036	1	0.0036	2.51	0.1521	
A ²	0.0010	1	0.0010	0.6818	0.4329	
B ²	0.0023	1	0.0023	1.59	0.2434	
C ²	0.0001	1	0.0001	0.0666	0.8029	
Residual	0.0115	8	0.0014			
Lack of Fit	0.0069	5	0.0014	0.9045	0.5713	not significant
Pure Error	0.0046	3	0.0015			
Cor Total	0.5782	17				
Std. Dev.	Mean	C.V. %	R ²	Adjusted R ²	Predicted R ²	Adeq Precision
0.0380	2.77	1.37	0.9800	0.9576	0.8950	26.4287

3.1 Surface Roughness

Table 3 shows the analysis of variances (ANOVAs) for surface roughness. The ANOVA table is widely employed to draw conclusions and present statistical information for further analysis and interpretation [15]. The ANOVA quadratic model considered the F-values and P-values of the predictive model for surface roughness in Table 3. The model terms were significant, as evidenced by the ANOVA table F-value for the model, which was 43.67, and the P-value, which was less than 0.0500. In this instance, each of the three machining parameters was relevant, and the same can be said of the relationship between the stand-off distance and the traverse speed. The fact that the lack of fit is not statistically significant indicates that the model accurately predicted the results. A result of 0.90 for the F-value for lack of fit indicates that the lack of fit does not significantly differ from the error itself. Table 3 and Figure 1 both illustrate the variation that exists between the actual and the predicted results. The values are in reasonable agreement given that the discrepancy between the adjusted R^2 (0.9576) and the predicted R^2 (0.8950) is less than 0.2. This model has an appropriate precision of 26.429, which makes it attractive because it is larger than 4, and it may be utilized to travel design space. Next, the equation model as in Equation (1) was developed based on the ANOVA in Table 3.

$$\text{Surface Roughness} = 2.79 + 0.1409A + 0.1210B - 0.1040C - 0.0962AB + 0.0263AC + 0.0213BC - 0.0190A^2 \quad (1)$$

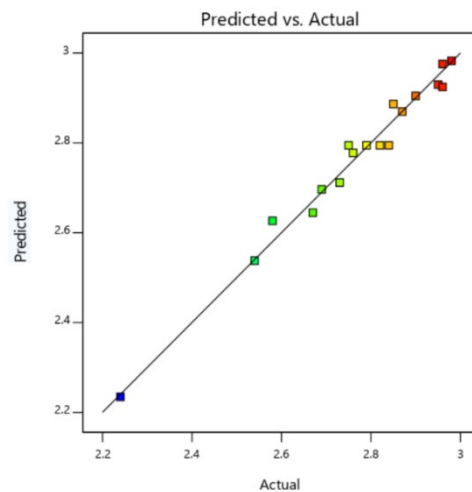


Fig. 1 Predicted versus actual results for surface roughness

A progressive increase in surface roughness had been obtained, as shown by the 3D surface plot in Figure 2, which went from 2000 mm/min to 3000 mm/min for traverse speed and from 5mm to 15mm for stand-off distance. It has been demonstrated that the traverse speed, as well as the stand-off distance, were directly proportional to the surface roughness, which was impacted by the kinetic energy that came from these two input parameters. A rougher surface is the result of a higher stand-off distance, which increases the jet's diameter before it impinges and decreases its kinetic energy, according to Azmir et al. [16]. When the traverse speed is increased, the amount of overlap machining that occurs decreases, but the amount of abrasive particle contact that occurs increases. A low value of surface roughness will result from the interaction of the slowest possible traverse speed and the lowest possible stand-off distance.

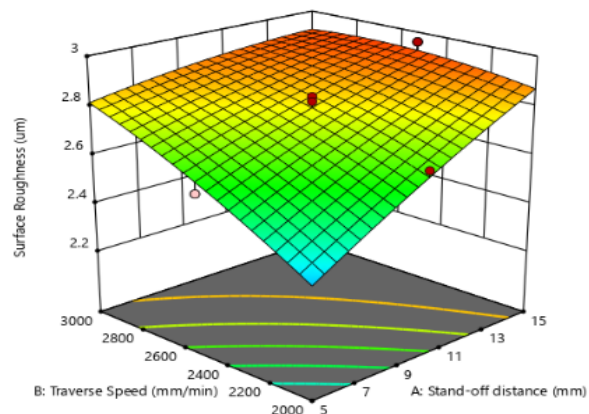


Fig. 2 The 3D surface of the effect of machining parameters on surface roughness

3.2 Kerf Width

Table 4 shows the analysis of variances (ANOVAs) for kerf width. The ANOVA quadratic model considered the model of prediction for the F and P-values that associated with the kerf width variable. If the F-value is 415.95 and the P-value was less than 0.0500, the model for the ANOVA table indicated that the model terms were significant. Only the stand-off distance and traverse speed variables with P-values that were lower than 0.0500 were considered for analysis. Because the abrasive flow rate has a P-value that is greater than 0.1000, the model terms cannot be considered significant. As a result, the flow rate of the abrasive does not affect the width of the kerf. In addition, a comparison of actual and predicted results may be found in Table 4 and Figure 3. The adjusted R² (0.9865) and the predicted R² (0.9802) are comparable to one another to within 0.2. Because this model has a sufficient precision of 54.011, which is greater than 4, it is desirable for use in design space navigation. Subsequently, a mathematical model represented by Equation (2) was established using the data obtained from the ANOVA in Table 4.

$$\text{Kerf Width} = 1.16 + 0.1680A - 0.0210B + 0.0040C \tag{2}$$

Table 4 ANOVA and fit statistics of kerf width analysis

Sources	Sum of squares	df	Mean square	F-value	P-value	
Model	0.2868	3	0.0956	415.95	< 0.0001	significant
A-Stand-off distance	0.2822	1	0.2822	1227.98	< 0.0001	
B-Traverse Speed	0.0044	1	0.0044	19.19	0.0006	
C-Abrasive flow rate	0.0002	1	0.0002	0.6961	0.4181	
Residual	0.0032	14	0.0002			
Lack of Fit	0.0032	11	0.0003			
Pure Error	0.0000	3	0.0000			
Cor Total	0.2900	17				
Std. Dev.	Mean	C.V. %	R ²	Adjusted R ²	Predicted R ²	Adeq Precision
0.0152	1.16	1.31	0.9889	0.9865	0.9802	54.0107

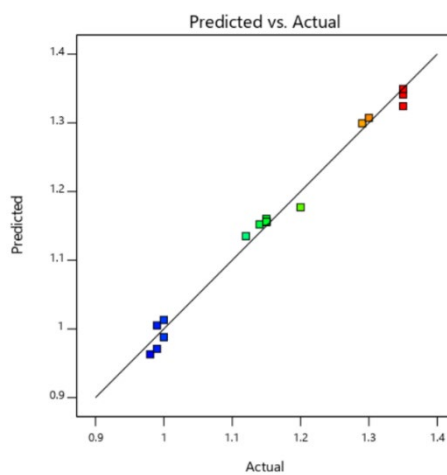


Fig. 3 Predicted versus actual results for kerf width

From the 3D surface plot in Figure 4, a gradual decrement of kerf width had been achieved from 2000 mm/min to 3000mm/min for traverse speed. This indicates that the kerf width will decrease when the traverse speed increases. This has been agreed by Pahuja et al. [17], that a lower traverse speed will cause a wider kerf width because of high power at low traverse speed. Then, kerf width will increase according to the increase in stand-off distance because a higher SOD causes the abrasive jet to enlarge, reducing the jet velocity and increasing

the cross-sectional area [18]. The abrasive flow rate, in this case, does not influence the kerf width so much. However, based on Patel et al. [14], a higher abrasive flow rate means an increase in the number of particles involved will generate more kinetic energy and be capable to enter the workpiece.

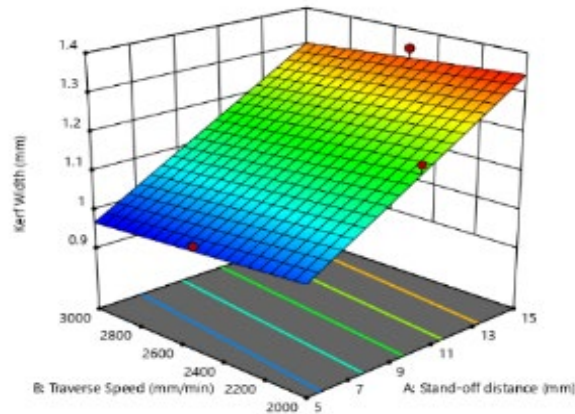


Fig. 4 The 3D surface of the effect of machining parameters on kerf width

3.3 Verification Experiment

The objective of the optimization analysis that was carried out in Design Expert Software was to acquire a small value for both the kerf width and the surface roughness. The optimal parameters that were sought after as a result of this analysis have been obtained. According to Table 5, the best circumstances for cutting are those that have a low stand-off distance and traverse speed value, but a high abrasive flow rate. The machining procedure has been carried out, and the kerf width and surface roughness of the finished product have both been measured and analyzed. This process was developed based on optimal parameters, which have already been investigated. The expected value was determined by making use of Equation (1) as well as Equation (2) which was established by ANOVA. Therefore, after cutting the material using optimal conditions, the result of its kerf width and surface roughness is in Table 6 below. The percentage error has been calculated by using Equation 3.

Table 5 Optimum machining parameters from optimization analysis

Stand-off Distance (mm)	Traverse Speed (mm/min)	Abrasive Flow Rate (kg/min)
5	2008.944	0.31759

The percentage error can be obtained by using the equation 3 below [19]:

$$\text{Percentage Error} = \left| \frac{v_A - v_E}{v_E} \right| \times 100 \tag{3}$$

Table 6 Results of optimization analysis and optimum experimentation

	Actual Value Observed, (v _A)	Expected Value, (v _E)	Percentage Error
Kerf Width (mm)	1.050	1.013	3.65%
Surface Roughness (µm)	2.45	2.240	9.38%

The actual value observed (v_A) is the value that gains from experimentation using the optimum machining parameter while the expected value (v_E) is the value that has been optimized by Design Expert software. As in Table 6, the percentage error between the expected value and actual value observed of cutting using the optimum machining parameter shares the view that the margin of error expressed as a percentage is a useful tool for assessing the reliability of experimental findings. This is because the percentage of error for both conditions is acceptable because it is below 10%. This shows that this research project is on the right track because the value is not far from the analysis in the software. Therefore, this parameter can be used in future work to cut glass fibre epoxy composite that produces a low kerf width and surface roughness.

3.4 Morphological Analysis

Non-optimal parameter settings have been used for morphological analysis using optical microscopes and scanning electron microscope (SEM) machines. The analysis's goal is to locate defects on the cut surface caused by non-optimal parameter conditions. made of glass fiber reinforced epoxy composites (GFREC) using AWJ machining. Fig. 5 below shows the image from Optical Microscopes for all three specimens of different machining parameters. The specimens tested are shown in Fig. 5(a) (SOD: 5mm, TS: 2000mm/min, and AFR: 0.31759kg/min), Fig. 5(b) (SOD: 10mm, TS: 2500mm/min, and AFR: 0.30171kg/min), and Fig. 5(c) (SOD: 15mm, TS: 2500mm/min, and AFR: 0.30171kg/min). Fig. 5(a) shows the ploughing occurs on the surface of the specimen. Ploughing, which results in inconsistent grooves and defects on the material's surface, happens because of poor machining conditions. Then, same goes for Fig. 5(b). There can be seen the fiber is pull-out and debonding. These defects risk the material's structural stability, possibly weakening it and impairing its performance. Lastly, delamination of which layers within the composite material might separate can be seen by the observations on the surface of Fig. 5(c). The study of the cut surfaces is strengthened, and a thorough comprehension of the faults is made possible by combining the data from optical and SEM equipment.

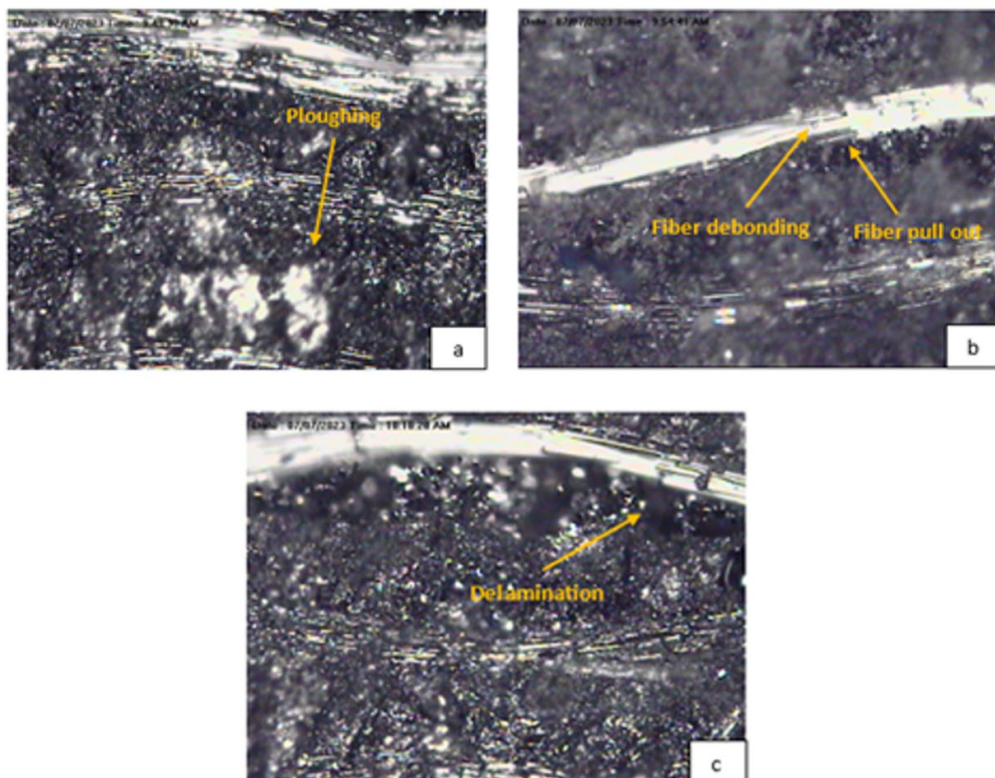


Fig. 5 Machined surface image using optical microscope (a) Ploughing; (b) Fiber debonding and fiber pull out; (c) Delamination

To support the morphological analysis from the observation of optical microscope, the SEM further strengthens the evidence that the defect was found on the cut surface. Fig. 6 shows the SEM image of GFREC. Fig. 6(a) reveals the ploughing on the surface. The image for the surface machined for Fig. 5(a) has been agreed by Fig. 6(a) in which there can be seen the ploughing occurs on the surface of the specimen. By cutting into the material and leaving behind grooves that are often shorter than the depth of cut, abrasive particles propelled by the water jet induce ploughing. Defects in microstructure frequently include fiber pull-out, debonding, and fracture. Due to factors such as a high traverse speed, which places a greater degree of strain on the fibers, and a high abrasive flow rate, which increases the mechanical interaction between the abrasive particles and the fiber, fibers embedded in a matrix material can be gradually pulled out, as shown in Fig. 6(b). Interfacial stress and matrix-fiber interactions cause fiber debonding and fracture during abrasive waterjet cutting. Debonding happens when the fibers and matrix material separate or weaken, while fracture occurs when the matrix material collapses under stress. Based on Fig. 6(c), where the stand-off distance is the highest, there are pits and delamination that occur on the surface of the cut specimen. Waterjet cutting can pit material due to its abrasiveness. As stand-off distance increases, cutting forces and energy are distributed more widely. Energy distribution may depress or hollow out some areas while leaving others undisturbed. Besides that, as the flow turbulence widened at a high stand-off distance, the surrounding fibers and matrix expand, allowing the crack generated by the abrasive embedment to deepen and cause delamination [20].

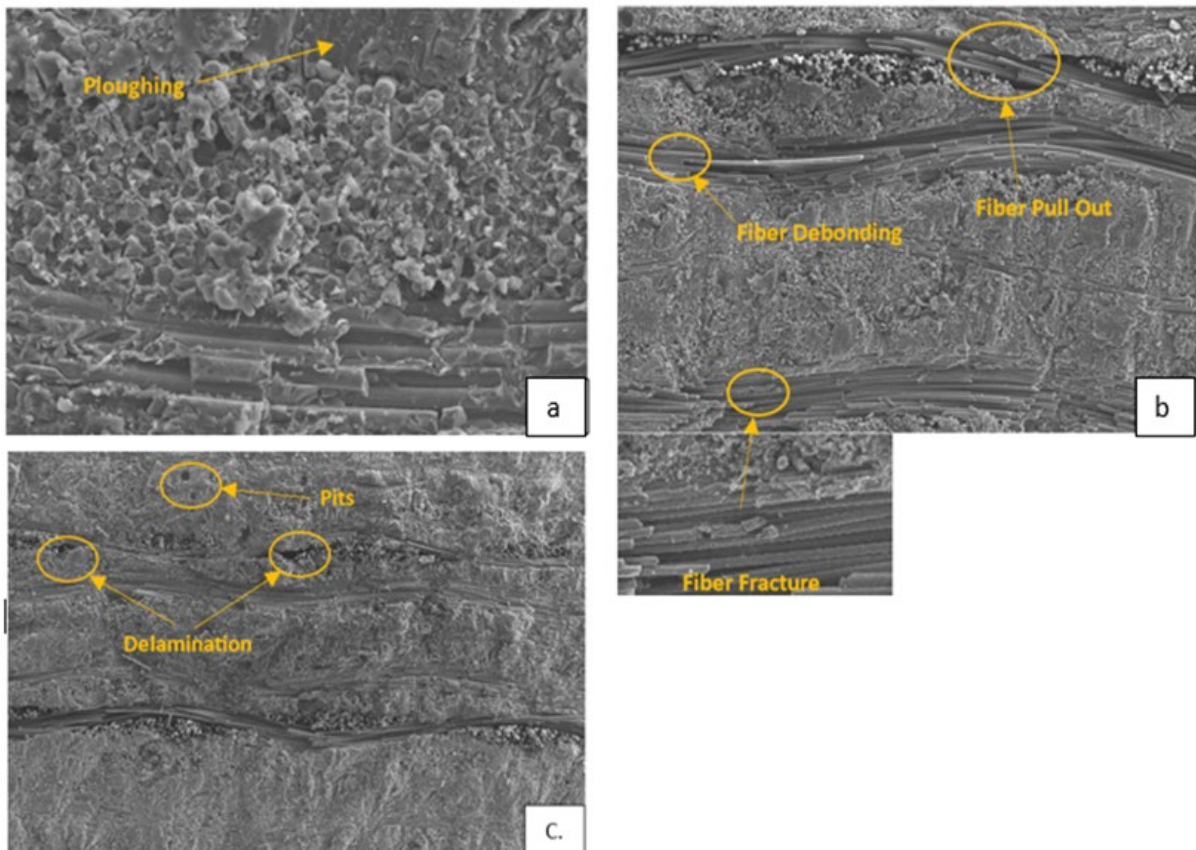


Fig. 6 SEM images of machined surface (a) Ploughing groove; (b) Fiber pull-out, debonding, and fracture; and (c) Pits and delamination on the surface

3. Conclusions

In conclusion, the objective to investigate the effects of traverse speed, stand-off distance, and abrasive flow rate on kerf width and surface roughness for abrasive water jet machining of glass fiber epoxy composite to find optimal cutting conditions has been achieved. The result showed that surface roughness decreases with the decremental value of traverse speed and stand-off distance while kerf width decreases with a higher value of traverse speed and lower value of stand-off distance. Based on experimental results, ANOVA analysis revealed that all three machining parameters and the interaction between traverse speed and stand-off distance significantly give influence surface roughness while stand-off distance and traverse speed is the only significant parameter that can influence kerf width. Then, the desired quality product can achieve by using the optimal cutting condition which has been agreed upon by the optimization analysis in this software (SOD: 5mm, TS: 2008.944mm/min, and AFR: 0.31759kg/min). Non-optimal cutting conditions can cause delamination, fibre pull-out, fibre debonding, fibre fracture, ploughing, and pits. To enhance the performance characteristics of the abrasive water jet machining process, it is necessary to conduct more tests with a larger number of process variables.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

Izdihar Tharazi: **draft manuscript preparation, analysis and interpretation of results** Wan Emri; **study conception and design and data collection** Muhamad Iltizam: **draft manuscript preparation and data collection** All authors reviewed the results and approved the final version of the manuscript.

References

- [1] Sathishkumar, T. P., Satheeshkumar, S., & Naveen, J. (2014). Glass fiber-reinforced polymer composites—a review. *Journal of reinforced plastics and composites*, 33(13), 1258-1275. doi: <https://doi.org/10.1177/0731684414530790>.
- [2] Karataş, M. A., & Gökkaya, H. (2018). A review on machinability of carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) composite materials. *Defence Technology*, 14(4), 318-326. doi: <https://doi.org/10.1016/j.dt.2018.02.001>.
- [3] Dahiya, A. K., Bhuyan, B. K., & Kumar, S. (2023). Abrasive water jet machining of glass fibre reinforced polymer composite: experimental investigation, modelling and optimization. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 17(4), 1933-1947. doi: <https://doi.org/10.1007/s12008-023-01312-w>.
- [4] Syazwani, H., Mebrahitom, G., & Azmir, A. (2016, February). A review on nozzle wear in abrasive water jet machining application. In *IOP Conference Series: Materials Science and Engineering* (Vol. 114, No. 1, p. 012020). IOP Publishing. doi: 10.1088/1757-899X/114/1/012020.
- [5] Singh, S., & SK Jain, P. (2013). An experimental and numerical investigation of mechanical properties of glass fiber reinforced epoxy composites. *Advanced Materials Letters*, 4(7), 567-572. doi: <https://doi.org/10.5185/amlett.2012.11475>.
- [6] Anu Kuttan, A., Rajesh, R., & Dev Anand, M. (2021). Abrasive water jet machining techniques and parameters: a state of the art, open issue challenges and research directions. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 43, 1-14. doi: <https://doi.org/10.1007/s40430-021-02898-6>.
- [7] Tripathi, D. R., Vachhani, K. H., Bandhu, D., Kumari, S., Kumar, V. R., & Abhishek, K. (2021). Experimental investigation and optimization of abrasive waterjet machining parameters for GFRP composites using metaphor-less algorithms. *Materials and Manufacturing Processes*, 36(7), 803-813. doi: <https://doi.org/10.1080/10426914.2020.1866193>.
- [8] Doreswamy, D., Shivamurthy, B., Anjaiah, D., & Sharma, N. Y. (2015). An investigation of abrasive water jet machining on graphite/glass/epoxy composite. *International Journal of Manufacturing Engineering*, 2015(1), 627218. doi: <https://doi.org/10.1155/2015/627218>.
- [9] Arola, D., & Ramulu, M. (1996). A study of kerf characteristics in abrasive waterjet machining of graphite/epoxy composite. doi: <https://doi.org/10.1115/1.2804897>.
- [10] Hreha, P., Radvanská, A., Hloch, S., Peržel, V., Królczyk, G., & Monková, K. (2015). Determination of vibration frequency depending on abrasive mass flow rate during abrasive water jet cutting. *The International Journal of Advanced Manufacturing Technology*, 77, 763-774. doi: <https://doi.org/10.1007/s00170-014-6497-9>.
- [11] MM, I. W., Azmi, A. I., Lee, C. C., & Mansor, A. F. (2018). Kerf taper and delamination damage minimization of FRP hybrid composites under abrasive water-jet machining. *The International Journal of Advanced Manufacturing Technology*, 94(5), 1727-1744. doi: <https://doi.org/10.1007/s00170-016-9669-y>.
- [12] Rajesh, M., Rajkumar, K., & Annamalai, V. E. (2021). Abrasive water jet machining on Ti metal-interleaved basalt-flax fiber laminate. *Materials and Manufacturing Processes*, 36(3), 329-340. doi: <https://doi.org/10.1080/10426914.2020.1832692>.
- [13] Perec, A., Pude, F., Kaufeld, M., & Wegener, K. (2017). Obtaining the selected surface roughness by means of mathematical model-based parameter optimization in abrasive waterjet cutting. *Strojniški vestnik-Journal of Mechanical Engineering*, 63(10), 606-613. doi: 10.5545/sv-jme.2017.4463.
- [14] Patel, Jignesh K., and Abdulhafiz A. Shaikh. "The influence of abrasive water jet machining parameters on various responses-a review." *International Journal of Mechanical Engineering and Robotics Research* 4, no. 1 (2015): 383. [Online]. Available: www.ijmerr.com.
- [15] Tharazi, I., Sulong, A. B., Muhamad, N., Haron, C. H. C., Tholibon, D., Ismail, N. F., ... & Razak, Z. (2017). Optimization of hot press parameters on tensile strength for unidirectional long kenaf fiber reinforced polylactic-acid composite. *Procedia engineering*, 184, 478-485. doi: <https://doi.org/10.1016/j.proeng.2017.04.150>.
- [16] Azmir, M. A., & Ahsan, A. K. (2008). Investigation on glass/epoxy composite surfaces machined by abrasive water jet machining. *Journal of materials processing technology*, 198(1-3), 122-128. doi: <https://doi.org/10.1016/j.jmatprotec.2007.07.014>.
- [17] Pahuja, R., Ramulu, M., & Hashish, M. (2019). Surface quality and kerf width prediction in abrasive water jet machining of metal-composite stacks. *Composites Part B: Engineering*, 175, 107134. doi: <https://doi.org/10.1016/j.compositesb.2019.107134>.

- [18] Vikas, B. G., & Srinivas, S. (2021). Kerf analysis and delamination studies on glass-epoxy composites cut by abrasive water jet. *Materials Today: Proceedings*, 46, 4475-4481. doi: <https://doi.org/10.1016/j.matpr.2020.09.683>.
- [19] Guang, W., Baraldo, M., & Furlanut, M. (1995). Calculating percentage prediction error: a user's note. *Pharmacological research*, 32(4), 241-248. doi: [https://doi.org/10.1016/S1043-6618\(05\)80029-5](https://doi.org/10.1016/S1043-6618(05)80029-5).
- [20] Singh, Q. J., & Rajamurugan, G. (2022). Experimental study on abrasive water jet machining of WCFC reinforced flax/wire mesh/hemp composite. *Journal of Industrial Textiles*, 52, 15280837221121961. doi: <https://doi.org/10.1177/15280837221121961>.