Investigation of the Impact of Abrasive Water Jet Machining Parameters on Delamination of Glass Fiber Reinforced Polymer Composites during Hole Drilling Process.

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Abstract. This study examines the effects of abrasive water jet (AWJ) drilling parameters on delamination, using a fractional factorial design (FFD) to identify significant factors and their interactions. Key process parameters, including water jet pressure, abrasive mass flow rate, traverse speed, standoff distance, laminate stacking sequence, and material thickness, were investigated. The results reveal that abrasive mass flow rate and material thickness are the most critical factors influencing delamination. Increased abrasive mass flow rate reduces delamination due to enhanced cutting efficiency, while greater material thickness exacerbates it due to higher stress concentrations. Additionally, a significant interaction between water jet pressure and abrasive mass flow rate was identified, highlighting the combined influence of these parameters. These findings underscore the potential of AWJ drilling as a precise machining technique and provide actionable insights for minimizing delamination in GFRP composite components.

1. Introduction

Glass fiber reinforced polymer (GFRP) composites are widely used in aerospace, automotive, marine, and construction industries due to their high strength-to-weight ratio, corrosion resistance, and superior fatigue performance. However, their heterogeneity and anisotropy pose challenges during machining, often causing defects like delamination, fiber pull-out, and matrix cracking, with delamination being the most critical as it compromises structural integrity. Abrasive water jet (AWJ) machining has emerged as an effective method for processing GFRP composites, offering advantages such as precision and minimal thermal damage. However, AWJ drilling, often required for hole creation, can lead to delamination, especially at the entry and exit regions. Understanding the factors influencing delamination in AWJ drilling is crucial for ensuring the reliability and quality of machined components. Delamination occurs when high machining forces separate the composite layers, and in AWJ machining, the high-pressure water jet can induce tensile stresses, causing cracks and delamination at the edges. Minimizing delamination is vital for maintaining the integrity and performance of composites in high-precision industries like aerospace, automotive, and marine. Controlling the machining parameters is key to improving outcomes.

Venkatesh Chenrayan et al. [1] studied delamination reduction in hybrid FRP composites during AWJM. They found that abrasive mass flow rate (AMFR) was the most important factor in minimizing delamination, followed by standoff distance (SOD). Using a hybrid Grey Relational Analysis-Principal Component Analysis (GRA-PCA) approach, they optimized the parameters: AMFR of 230 g/min, hydraulic pressure of 75 MPa, SOD of 2 mm, and traverse speed of 600 mm/min. A confirmation experiment showed a 33.9% reduction in delamination compared to random settings, offering valuable insights for minimizing delamination in AWJM of FRP composites. Meltem Altin Karataş et al. [2] studied delamination during AWJ drilling of carbon fiber-reinforced polymer (CFRP) composites with three fiber orientations: [0°/90°]s (M1), [+45°/−45°]s (M2), and [0°/45°/90°/−45°]s (M3). They found delamination was more severe at the hole entry than the exit for all orientations, with water pressure (WP) being the most influential factor, affecting 66.6–82.4% of delamination. Increasing WP reduced delamination damage. The optimal parameters for minimizing delamination at both hole entry and exit were WP of 5300 bar, feed rate of 750 mm/min, SOD of 1 mm, and hole diameter of 10 mm. The delamination factor (Fd) ranged from 1.572 (maximum) to 1.029 (minimum), achieved with the M2 composite and [+45°/−45°]s orientation. In the study conducted by Gondi Krishnaprasad et al. [3], the aim was to investigate the influence of process parameters on minimizing delamination during AWJM of carbon and glass fiber composites. The results revealed that WP and traverse speed (TS) were the major influencing parameters. The study found that damage-free holes and a lower delamination factor were achieved by increasing WP and decreasing TS. This indicates that AWJM can be an effective technique for minimizing delamination in both carbon and glass fiber composites. The study by Anil Kumar Dahiya et al. [4] investigates the impact of process parameters on delamination during AWJM of GFRP composites. The research reveals that delamination tends to increase with higher TS and WP, with the most significant delamination observed at the bottom portion of the machined samples. The delamination effect was measured using scanning electron microscopy (SEM), providing detailed insights into the damage caused during the machining process. Raju Kumar Thakur et al. [5] investigated the impact of graphene nanoplatelets (GNPs) on the delamination factor of GFRP composites during AWJ drilling. They found that adding GNPs improved interfacial adhesion, reducing delamination at both the entry and exit points. Delamination was more significant at the entry side. The lowest delamination factor occurred with 0.25 wt% GNPs, low TS, and high WP, resulting in a Fd of 1.2141 at the entry and 1.1223 at the exit. The study showed that GNP content had a significant impact on delamination, with 57.34% and 58.93% influence on entry and exit DF, respectively. A study made by Anil Kumar Dahiya et al. [6] focused on the impact of process parameters on delamination during AWJM of GFRP composites. The study investigates the influence of four parameters—WP, SOD, TS, and AMFR—on maximum delamination length (Max. DLL). Using response surface methodology (RSM) and central composite design (CCD), the research finds that delamination decreases with an increase in AMFR and a decrease in TS. The optimization results, using the desirability function, show an acceptable combined desirability value of 0.959 for minimizing Max. DLL, with a percentage error of less than 4.318% at the optimum process parameters. A study by J. Schwartzentruber et al. [7] examined delamination in carbon fiber/epoxy laminates during AWJ cutting through experimental and numerical methods. Using a fluid-structure interaction model and cohesive zone modeling, delamination along ply interfaces was predicted and found to depend primarily on normal interlaminar stress. Numerical simulations and 3D x-ray micro-tomography confirmed that delamination was more pronounced at the cutting front compared to the side walls due to higher forces exerted at the cutting front. A moisture uptake methodology was applied to measure delamination experimentally, incorporating a six-factor Taguchi design of experiments with variables such as WP, SOD, AMFR, TS, mixing tube size, and fiber orientation. The results showed that TS and AMFR had significant effects on reducing delamination, while larger mixing tube sizes increased delamination damage. The findings aligned well with the numerical predictions, validating the trends observed in the simulations. A study by P. F. Mayuet et al. [8] studied delamination during AWJM of CFRP plates, focusing on cutting parameters. Using Scanning Optical Microscope (SOM) and SEM, they found that AMFR, abrasive size, and timing were key factors affecting delamination. Higher WP worked well for thicker materials, while intermediate TS and increased AMFR reduced delamination. The study emphasizes the need for further research on SOD to better understand its impact on delamination and provides insights for optimizing AWJM parameters to minimize defects in CFRP machining. D.K. Shanmugam et al. [9] studied delamination in graphite/epoxy composites during AWJM. They identified delamination as a critical defect caused by the initial shock wave impact, which creates cracks that propagate due to water penetration and abrasive embedment. A semi-analytical energy conservation model was developed to predict delamination, accurately estimating the maximum delamination length and matching experimental results. This model offers practical guidance for controlling delamination in AWJ machining of layered composites. The study by Ajit Dhanawade et al. [10] studied delamination in AWJM of carbon epoxy composites using RSM. They analyzed the impact of four process parameters—WP, TS, SOD, and AMFR—on delamination. SEM observations revealed that delamination decreased with higher WP and AMFR, and lower TS and SOD. A mathematical model developed to predict delamination aligned well with experimental results, and optimizing the parameters effectively minimized delamination, ensuring defect-free machining. Irina Wong MM et al. [11] studied delamination in abrasive water jet machining (AWJM) of hybrid carbon/glass fiber-reinforced polymer composites. Experimental results and statistical analyses reveal that delamination damage is more severe on the entrance side compared to the bottom side of the machined composite. Among the process parameters, AMFR is the most influential factor affecting delamination, followed by TS and WP. Minimizing delamination can be achieved by increasing the kinetic energy of the AWJ while operating at lower cutting speeds. The study establishes empirical relationships using RSM, confirming that the developed regression models accurately predict delamination damage, with a variance of less than 5% compared to experimental results. The study by K. Siva Prasad et al. [12] investigated delamination during drilling of GFRP composites, focusing on process parameters like feed rate, spindle speed, thickness, and fiber orientation. They examined peel-up and push-down delamination mechanisms to identify optimal cutting conditions. The results showed that peel-up delamination is mainly influenced by material thickness, followed by feed rate and fiber orientation, while push-down delamination is most affected by feed rate and thickness. Optimization using Taguchi's S/N ratio analysis and ANOVA revealed that feed rate has the greatest impact on delamination. A regression model to predict delamination showed over 98% accuracy, highlighting the importance of selecting proper process parameters to improve hole quality in GFRP composites. R.K. Thakur et al. [13] studied delamination in hybrid carbon/glass fiber composites during AWJM, focusing on jet entry and exit. They examined the effects of WP, SOD, and TS on delamination, using ANOVA for statistical analysis. The results showed that delamination increases with higher TS and SOD but decreases with higher WP. TS was found to be most influential at the entry, while SOD had a greater effect at the exit. Delamination was consistently more severe at the entry. The study highlights the importance of optimizing process parameters to minimize delamination in AWJ machining of hybrid composites.

The reviewed literature provides valuable insights into the mechanisms and effects of delamination during machining of fiber-reinforced polymer composites (FRPC), with specific emphasis on the influence of machining parameters. However, most studies primarily focus on individual parameters and their effects, offering limited exploration of parameter interactions, which are crucial for understanding the complex nature of machining processes. Additionally, while research on hybrid and specific composite systems like graphite/epoxy and carbon/glass composites is well-documented, there is a noticeable gap in the systematic study of GFRP composites under AWJM. This study aims to address these gaps by investigating GFRPC as the material of interest and employing a robust experimental design to evaluate both the main and interaction effects of key machining parameters, providing a comprehensive understanding to optimize the process.

2. Methodology

2.1. input parameters and responses:

The input parameters selected for this study include water jet pressure (WP), abrasive mass flow rate (AMFR), traverse speed (TS), standoff distance (SOD), laminate stacking sequence (SS), and material thickness (t). These parameters were chosen based on their significant influence on the abrasive water jet machining (AWJM) process and their impact on the quality of the drilled holes in glass fiber reinforced polymer (GFRP) composites. The ranges and levels of the input parameters are selected based on literature and practical constraints of the AWJM process. The levels correspond to the low (-1) and high (+1) values used in the experimental design is presented in Table.1. To quantify and evaluate delamination in this study, the delamination factor (Fd) is used. The delamination factor is a numerical value calculated by equation.1 that represents the extent of delamination relative to the hole diameter, with higher values indicating more significant delamination. The factor is typically determined by measuring the delaminated diameter and comparing it to the original hole diameter as shown in figure.1.

Table 1: Input parameters levels

Parameter	Units	Low Level (-1)	High Level (+1)
Water Jet Pressure	Bar	1500	3000
Abrasive Mass Flow Rate	g/min	114	627
Traverse Speed	mm/min	250	1500
Standoff Distance	mm	1	3
Laminate Stacking Sequence	-	0/90	0/45/90/45
Material Thickness	mm	2	3

$$Fd = \frac{D_{max}}{D_0} \qquad (1)\ [5]$$

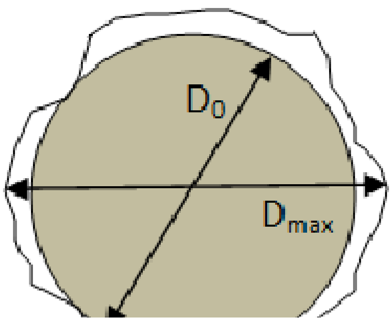


Figure 1:Delamination Factor

2.2.Design of experiment:

The purpose of using a well-structured DOE is to efficiently explore the impact of multiple input factors on the delamination factor, while minimizing the number of experimental runs required. This approach is particularly important for reducing time and cost in experimental setups, as well as for understanding the main effects and interactions between parameters. In this study, a **half fractional factorial design** with two replicates was used to systematically investigate the effects of various process parameters on the delamination factor and the design matrix is shown in table.2.

2.3. Experimental work:

2.3.1 specimens preparation:

The Glass Fiber Reinforced Polymer (GFRP) composites used in this study were fabricated using the hand layup technique. The composite was then cured at room temperature with the assistance of a vacuum bag, which applied pressure to the laminate, ensuring uniform resin distribution and minimizing air voids. The physical and mechanical properties of S-Glass fiber and resin is presented in tables 3 and 4 respectively.

2.3.2 Experimental setup:

A high-pressure AWJM system capable of delivering water mixed with abrasive particles at controlled flow rates and pressures. The machine used in this study was equipped with adjustable settings for

Table 2: Design Matrix

Standard order	WP (bar)	AMFR (g/min)	SOD (mm)	TS (mm/min)	t (mm)	SS
1	1500	114	1	265	2	[0,90]ns
[illegible]	[illegible]	114	1	265	2	[+45,-45/0,90]ns
[illegible]	[illegible]	627	1	265	2	[+45,-45/0,90]ns
4	3000	627	1	265	2	[0,90]ns
5	1500	114	3	265	2	[+45,-45/0,90]ns
6	3000	114	3	265	2	[0,90]ns
7	1500	627	3	265	2	[0,90]ns
[illegible]	3000	627	3	265	2	[+45,-45/0,90]ns
[illegible]	[illegible]	114	1	1500	2	[+45,-45/0,90]ns
10	3000	114	1	1500	2	[0,90]ns
11	1500	627	1	1500	2	[0,90]ns
12	3000	627	1	1500	2	[+45,-45/0,90]ns
13	1500	114	3	1500	2	[0,90]ns
14	3000	114	3	1500	2	[+45,-45/0,90]ns
15	1500	627	3	1500	2	[+45,-45/0,90]ns
16	3000	627	3	1500	2	[0,90]ns
17	1500	114	1	265	3	[+45,-45/0,90]ns
18	3000	114	1	265	3	[0,90]ns
19	1500	627	1	265	3	[0,90]ns
20	3000	627	1	265	3	[+45,-45/0,90]ns
21	1500	114	3	265	3	[0,90]ns
22	3000	114	3	265	3	[+45,-45/0,90]ns
23	1500	627	3	265	3	[+45,-45/0,90]ns
24	3000	627	3	265	3	[0,90]ns
25	1500	114	1	1500	3	[0,90]ns
26	3000	114	1	1500	3	[+45,-45/0,90]ns
27	1500	627	1	1500	3	[+45,-45/0,90]ns
28	3000	627	1	1500	3	[0,90]ns
29	1500	114	3	1500	3	[+45,-45/0,90]ns
30	3000	114	3	1500	3	[0,90]ns
31	1500	627	3	1500	3	[0,90]ns
32	3000	627	3	1500	3	[+45,-45/0,90]ns

Property	Resin (CR83)	Hardener (CH83-10)	Mixture
Individual components	CR83	CH83-10	
Mixing ratio, parts by weight	100	30	
Mixing ratio, parts by volume	100	36	
Viscosity, 25°C (mPa.s)	610	<10	155
Density, 25°C (g/ml)	1.14	0.95	1.15
Potlife (min)			300
Tensile strength (MPa)			86

Table 3: S-Glass fiber physical and mechanical properties

Property	Value
Density	2.49 g/cm³ (155.5 lb/ft³)
Tensile Strength	4750 MPa (689 ksi)
Modulus of Elasticity	89 GPa (12,910 ksi)
Elongation at Break	5.40%
Poisson's Ratio	0.22

Tensile E-modulus (GPa)	3.1
Elongation Percent at break	7.9
Glass transition temperature (°C)	81

Table 4: Matrix physical and mechanical properties

water pressure, abrasive mass flow rate, traverse speed, and standoff distance, the experimental setup is shown in figure.2.

2.3.3 Measuring Tools and Techniques:

A high-resolution digital microscope was employed to capture detailed images of the holes drilled in the specimens. These images were then processed using ImageJ software as shown in figure.3 to enhance clarity of the images, allowing for precise measurement of the maximum damage diameter.

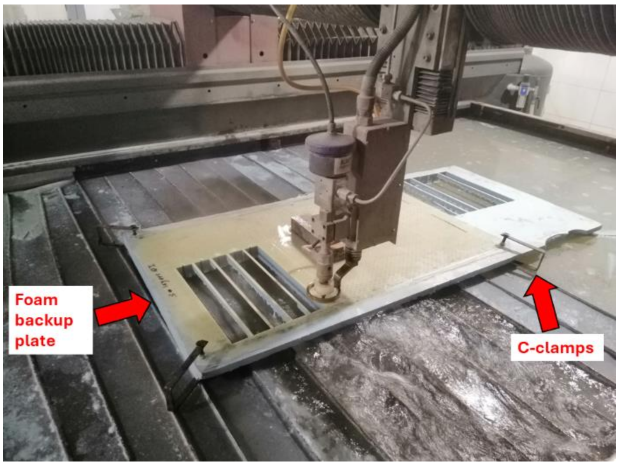


Figure 2: Experimental Setup

3. Results and discussion:

During observation of the drilling process, it was noted that delamination damage occurs suddenly at the beginning of the process when the jet first impacts the workpiece. As a result, it was decided to exclude traverse speed (TS) from the analysis, as it does not contribute to the creation of delamination. Including TS in the analysis could potentially mislead the results. The results of Fd are tabulated in Table 5.

3.1 Analysis of variance (ANOVA):

ANOVA is used to assess the impact of various parameters on delamination during abrasive water jet drilling. By partitioning the total variability in the responses into components attributable to the factors and their interactions, ANOVA determines which parameter significantly affect delamination. The F-statistic and p-value are used to test the significance, with a p-value less than 0.05 indicating a significant effect.

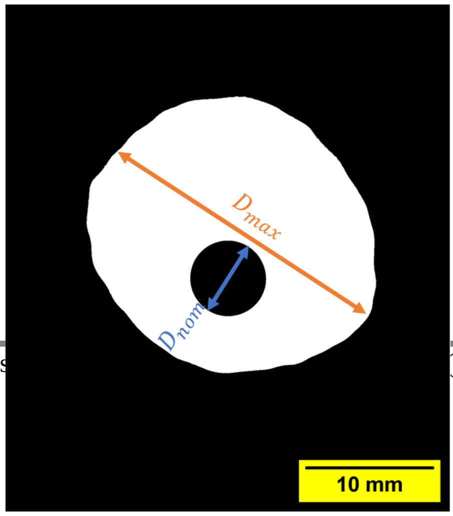


Table 6: ANOVA Table

Table 5: ANOVA table

(a) (b)

Figure 3: Hole image (a) before processing, (b) after processing

This helps identify which parameters and their interactions most influence delamination, providing valuable insights for optimizing the drilling process. ANOVA results are summarized in table.6. The ANOVA results indicate that AMFR and material thickness are the most significant main effects influencing delamination (Fd). Additionally, a notable interaction between water pressure WP and AMFR was observed, suggesting that the combined effect of these parameters plays a crucial role in delamination formation.

These findings highlight the importance of carefully controlling AMFR and material thickness, as well as considering the interplay between WP and AMFR when optimizing abrasive water jet drilling processes for minimal delamination.

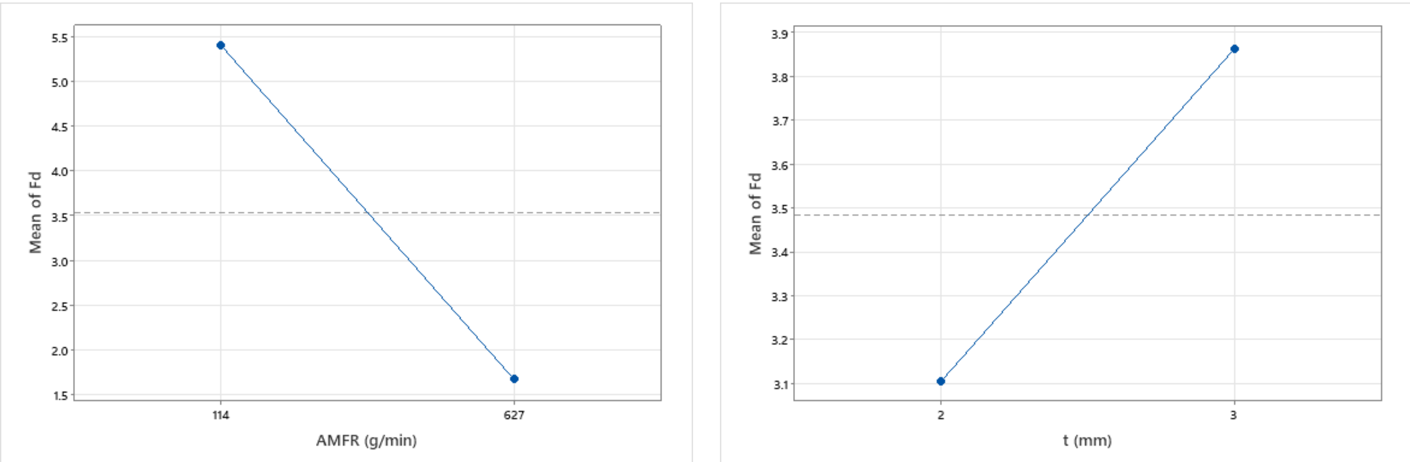
Source	**Fd**	
	F-Value	**P-Value**
WP	1.89	0.176
AMFR	167.76	**<0.001**
SOD	0.17	0.683
t	8.13	**0.006**
SS	1.52	0.224
WP*AMFR	11.39	**0.001**
WP*SOD	0.11	0.738
WP*t	<0.01	0.983
WP*SS	2.77	0.102
AMFR*SOD	0.19	0.666
AMFR*t	3.64	0.063
AMFR*SS	0.02	0.902
SOD*t	0.01	0.909
SOD*SS	0.01	0.908
t*SS	1.09	0.302

Table 6: The Results of delamination factor

StdOrder	**Fd**		**StdOrder**	**Fd**	
1	[illegible]07	4.4[illegible]	**17**	8.46	8.65
2	4.54	5.2[illegible]	**18**	5.62	5.95
3	1.59	1.4[illegible]	**19**	1.03	1.03
4	[illegible]	1.3[illegible]	**20**	1.42	3.47
5	[illegible]	5.9[illegible]	**21**	4.53	7.02
6	[illegible]9	3.8[illegible]	**22**	2.33	6.29
7	[illegible]	1.3[illegible]	**23**	1.06	3.22
8	[illegible]	1.7[illegible]	**24**	2.49	2.63
9	[illegible]	4.8[illegible]	**25**	7.93	4.07
10	[illegible]	2.7[illegible]	**26**	3.73	3.24
11	[illegible]	1.5[illegible]	**27**	1.15	1.01
12	[illegible]	1.7[illegible]	**28**	2.14	2.28
13	[illegible]69	5.0[illegible]	**29**	6.70	6.52
14	5.35	3.83	**30**	6.49	5.80
15	2.35	1.47	**31**	1.00	1.39
16	1.39	1.78	**32**	3.14	1.82

3.2 Main and interaction plots:

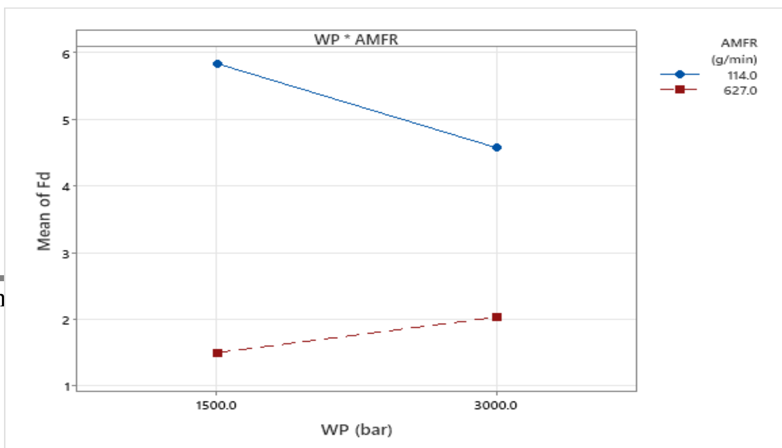
Main effect plots visually represent the relationship between each parameter and the response, illustrating how the response increases or decreases as the parameter level changes. These plots help in understanding the proportionality between the parameter and the response. Interaction plots, on the other hand, reveal how the effect of one parameter on the response is influenced by the levels of another parameter. They highlight the combined impact of parameters, showing whether changes in one parameter modify the trend observed with another, indicating any significant interactions between the parameters.Main effects plots of AMFR and material thickness are represented in figure.3 (a) and (b)



(a) (b)

Figure 4: Main effects plots (a) AMFR, (b) material thickness

The interaction between WP and AMFR is illustrated in figure.4. It shows that the inverse proportionality between Fd and WP at low



level of AMFR is changed to be direct proportionality at high level of AMFR

Figure 5: Interaction effects plot between WP and AMFR

3.3 Physical interpretation of the results:

3.3.1 effect of AMFR on Fd:

When the abrasive mass flow rate (AMFR) increases, the density of abrasive particles within the water jet also increases. This results in a higher concentration of cutting particles impacting the surface of the material, which enhances the cutting efficiency. With more efficient material removal, the jet can cut through the fibers and matrix of the composite more cleanly, reducing the stress waves and mechanical disruptions that typically lead to delamination. Furthermore, the increased energy transfer from the jet to the material minimizes the occurrence of uncut fibers that could otherwise pull up adjacent layers, mitigating delamination damage. These results align with the findings of [4], [6] and [9].

3.3.2 Effect of material thickness on Fd:

Delamination increases with material thickness because thicker laminates present a greater resistance to the penetrating water jet, causing higher energy dissipation and stress accumulation near the entry point. This concentrated stress increases the likelihood of interlaminar cracks as the jet struggles to maintain cutting efficiency through the additional layers. The higher bending stiffness of thicker materials further amplifies these stresses, making delamination more prominent. These results align with the findings of [5], [6], [9] and [11].

3.3.3 Interaction between WP and AMFR affecting Fd:

From figure.5 it was found that interaction between WP and AMFR is significantly influenced the Fd. At lower levels of AMFR, the relationship between WP and Fd was inversely proportional, meaning that increasing WP led to a decrease in Fd. This could be attributed to the higher pressure causing a more concentrated and forceful water jet, which likely helped to compact the fibers and reduce the likelihood of delamination. On the other hand, at higher levels of AMFR, the relationship between WP and Fd became directly proportional, where increasing WP resulted in a higher Fd. This can be explained by the increased abrasive flow intensifying the cutting action, causing greater material removal and more fiber disruption at the hole edges, which enhances delamination. The interaction between these two parameters suggests that the abrasive flow rate plays a key role in modulating the effect of water pressure on the delamination process, and careful optimization of both parameters is necessary to minimize delamination in AWJ machining.

4. Conclusion

In conclusion, the study highlights the significant impact of process parameters on delamination during abrasive water jet drilling. Abrasive mass flow rate and material thickness emerge as critical factors, with increased abrasive flow reducing delamination due to enhanced cutting efficiency and reduced fiber bending, while greater material thickness exacerbates delamination due to higher stress concentrations. Additionally, a significant interaction between water pressure and abrasive mass flow rate was observed, indicating that their combined effect plays a crucial role in influencing delamination behavior.

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Nomenclature:

AWJM	Abrasive water jet machining
GFRP	Glass fiber reinforced polymer
WP	Water pressure
TS	Traverse speed
SOD	Stand off distance
AMFR	Abrasive mass flow rate
SEM	Scaning electron microscope
Fd	delamination factor
ANOVA	Analysis of variance
RSM	Response surface methodology