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EXPERIMENTAL INVESTIGATION OF DELAMINATION DAMAGE FOR GLASS FIBER-REINFORCED POLYMER COMPOSIT-E DURING ABRASIVE WATERJET MACHINING

H. HANIZAM[1,*], N. H. A. MAZLI[1], M. I. RAMLI[2],
A. H. ABDUL RASIB[1], N. BAHIYAH BABA[3]

[1]Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[2]Fakulti Teknologi dan Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[3]Faculty of Engineering Technology, University College TATI (UC TATI), Teluk Kalong, Kemaman 24000, Terengganu.
*Corresponding Author: hanizam@utem.edu.my

Abstract

Delamination damage of glass fibre-reinforced polymer (GFRP) composite in abrasive waterjet machining (AWJM) is still a major issue. The main AWJM parameters that have a significant impact on delamination vary depending on the type of GFRP especially for marine applications. Hence, a Taguchi method of L8 orthogonal array design of experiment carried out to optimize the traverse speed (TS), standoff distance (SOD) and waterjet pressure (WP) parameters of AWJM on 8-layer GFRP ship panel. The results revealed that SOD has the most significant impact on delamination damage and followed by WP and TS were ranked 2 and 3, respectively. The optimized combination was at parameters of SOD (5 mm), WP (150 MPa) and TS (38 mm/min), which gave a minimum delamination radius of 6.25 mm. The delamination trend decreases at the increase of SOD and TS but increases at the higher of WP. The delamination damage starts at the piercing instance and travels further into the fibre layers during cutting. Further investigations on controlling the piercing factors shall help to reduce this damage.

Keywords: Abrasive waterjet machining, Delamination, Glass fibre reinforced polymer, Process optimization, Taguchi method.

1. Introduction

Glass fibre reinforced polymer (GFRP) composite is suitable for products in many industries, especially in shipbuilding and marine, due to its waterproofing, low weight, high strength properties and easy manufacturability compared to other traditional materials such as wood and sheet metal [1, 2]. Although a single mould shall produce the base of a boat without any joints, some parts or panels still need to be joined and bolted together. These panels need cutting, trimming and drilling to allow fitting, nuts and bolts that introduce stress concentration to internal fibre layers and cause splitting or delamination [3]. Hence, delamination damage during machining in composites is common and significantly reduces the structural strength and is a source of crack failure during service [4-7]. Gu et al. [8] and Shanmugam et al. [9] have summarized the mechanism of delamination due to the elastic response of the material in contact with a sudden pressure of the waterjet and continues with traverse shear stress causing downward bending of the composite layers.

Advanced technologies, such as laser, electro-erosion and abrasive waterjet have been used recently for composite materials machining because they permit better dimensional control, accuracy and time management [10]. However, delamination damage is still a big issue due to the nature of the composite layers. Therefore, optimum cutting parameters are still actively carried out to minimize failures such as fibre rupture, de-bonding, and stress concentration that led to delamination [11]. Amongst these cutting technologies, abrasive waterjet machining (AWJM) is employed widely for GFRP composite machining due to its practicality and cost-effectiveness. AWJM process parameters such as water pressure, traverse speed, stand-off distance, abrasive flow rate, and abrasive size are significant in the minimizing of delamination issue [12].

A Taguchi method is one of the prominent tools used in process optimization due to its robustness, timely and economically [13, 14]. Krishnaprasad et al. [15] employed Taguchi's L16 orthogonal array (OA) to optimize the AJWM's abrasives mass flow rate (AMFR), standoff distance (SOD), traverse speed (TS), and waterjet pressure (WP) using MINITAB software on GFRP. The results show waterjet pressure and traverse speed have the most significant impact on the delamination problem. At higher WP and lower TS, produce smaller delamination areas. On the other hand, abrasive flow and SOD have no significant impact on delamination. However, Vijayan et al. [13] reported that AMFR and SOD do impact on delamination damage. The delamination decreases with the decrease in SOD and the increase in AMFR. Moreover, according to the experiment results conducted by Reddy and Venkatesh [16], all four parameters cause an increase in delamination together with the increased setup values.

Dahiya et al. [17] conducted an experiment using Taguchi's L16 OA on a 67% glass fibre in GFRP for delamination effect with the parameters ranges at WP (200 – 350 MPa), SOD (1 – 4 mm), TS (50 – 200 mm/min) and AMFR (200 – 800 g/min). As a result, TS and AMFR have been the most influential on delamination and on the other hand, WP and SOD have a minor impact. The lowest delamination length obtained was 0.97 mm at TS (100 mm/min), AMFR (600 g/min), WP (200 MPa) and SOD (2 mm). Moreover, Murthy et al. [18] studied the waterjet cutting on a jute–epoxy fibre composite delamination issue using Taguchi L27 OA at TS (20 – 30 mm/min), SOD (2 – 4 mm) and AMFR (0.25 – 0.35 kg/min).

The AMFR has the greatest, SOD was moderate, and TS showed the least impact on delamination. The lowest delamination area obtained was 52.6 mm^2 with the AMFR (0.25 kg/min), SOD (4 mm) and TS (20 mm/min). Reddy and Venkatesh [16] have studied the impact of waterjet cutting on delamination for glass laminate aluminium-reinforced epoxy at various thicknesses. The lowest delamination of 0.456 mm for 12 mm thickness was obtained at WP (240 MPa: moderate pressure), TS (6 mm/min: highest speed), AMFR (100 g/min: lowest rate) and SOD (3 mm: moderate height). Finally, Karatas et al. reported that WP and SOD are the most effective parameters in determining the delamination factor of GRFP.

Although, many studies have been conducted to optimize all four parameters of AWJM on GFRP, the ranking of these parameters that have a significant impact on delamination issues is not the same and varies based on the nature of composites. Therefore, the objective was to run experiments on minimizing delamination damage during waterjet machining on the 8 layers/6 mm thickness GFRP boat panels. Taguchi's design of experiments (DOE) of the L8 orthogonal array is used in the study as it requires fewer runs and at a reduced cost. Two levels' parameters of traverse speed, waterjet pressure, and nozzle standoff height were selected and Minitab 18 software to run the DOE.

2. Experimental Procedures

2.1. Materials

Multiple layers of E-Glass fibre LT-1200 and a single layer of 450 g emulsion-bound chopped strand mat (CSM-450) were used as reinforcements. A polyester resin was employed as the matrix phase and finished with a polyester surfacing veil/tissue on top of the composite as shown in Table 1. The overall thickness of the composite was 6 mm for boat fabrication and repair panel purposes.

Table 1. Fiber glass composite layers' configuration.

Layer	Type of material	Description
1	Polyester surfacing Veil/Tissue	Dry Fit
2	CSM 450	
3	LT 1200	
4	LT 1200	
5	LT 1200	
6	LT 1200	
7	LT 1200	
8	LT 1200	

2.1.1. Composite fabrication

The 8-layer composite (120 cm × 120 cm) was prepared using a wet hand-layup method on a flat mould. A release agent was applied to prevent the part from sticking before the criss-cross reinforced fibre laying, as shown in Fig. 1. Then, a controlled amount of resin on each layer and impregnate the fibres was applied using a roller, brush and squeegee. Finally, an air evacuation process using a vacuum bagging technique of 25 Hg (vacuum pressure) was to prevent any undesirable void trapped within the layers and simultaneously curing for 10 hours at an ambient temperature of 27 °C.

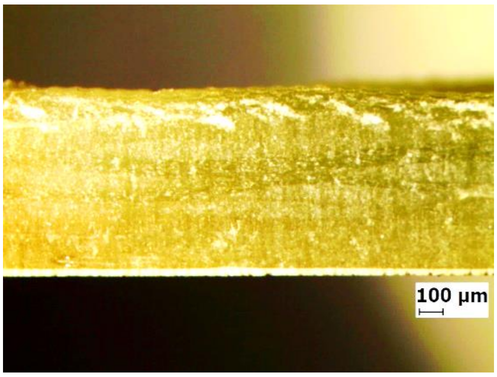


Fig. 1. 8-layer GFRP composite.

2.2. Design of experiment

The machining experiments were conducted using a FLOW MACH 2 abrasive waterjet machine (AWJM) of working table size (1.3 m × 1.3 m) as shown in the schematic diagram of Fig. 2. According to many, traverse speed, stand-off distance (away from a composite surface) and waterjet pressure were significant factors in AWJM and therefore been selected for this experiment as shown in Table 2. Other parameters, for instance, abrasive size (80 mesh), abrasive flow rate (0.5 g/min), and nozzle size (1 mm) were fixed. A Taguchi method is an appropriate parameters optimization tool to be used when dealing with a few significant variables. Therefore, according to Taguchi's L8 orthogonal array of 3 factors and 2-level developed by MINITAB software, a minimum of 8 experiments are only required as shown in Table 3. Since the goal of experiment is to minimize the delamination, smaller is better of signal-to-noise (S/N) being used to evaluate the significant of process parameters.

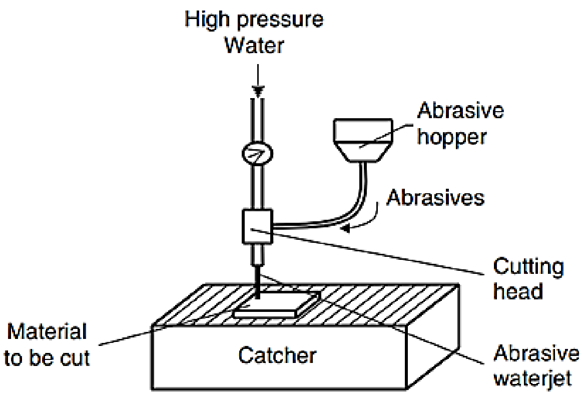


Fig. 2. Schematic of AWJM.

Table 2. Taguchi L_8 AWJM parameter settings.

Factor	Traverse speed (mm/min)	Stand-off height (mm)	Factor
High	76	5	300
Low	38	1	150

Table 3. Taguchi L_8 orthogonal array.

Exp.	Traverse speed (mm/min)	Stand-off height (mm)	Waterjet pressure (MPa)
1	76	5	300
2	38	1	150
3	76	1	150
4	38	5	300
5	76	1	300
6	38	5	150
7	76	5	150
8	38	1	300

A total of 10 holes with 3 mm diameter were cut through for each experiment from the same 8 mm thickness composite plate to prevent any process or material variations as depicted in Fig. 3. The average delamination radius value was calculated from 10 holes for each experiment using a stereomicroscope Nikon SMZ 745T.

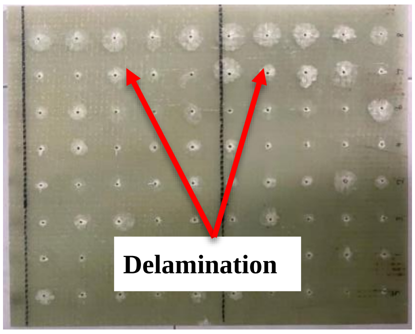


Fig. 3. Series of 10 holes by AWJM.

The outermost point of delamination of a bright contrast compared with the darker-based composite from the hole centre was measured as the delamination radius for each hole and indicated as CR as shown in Fig. 4. The CR33 and CR1 are taken from random samples to indicate the maximum radius measurement method clarification. The delamination radius is taken instead of the delamination area because further service failures of an existing delamination defect will be propagated and influenced by the furthest crack [13, 19].

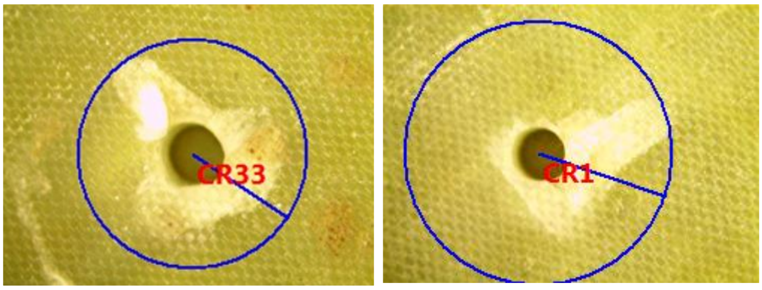


Fig. 4. Delamination radius measurement method.

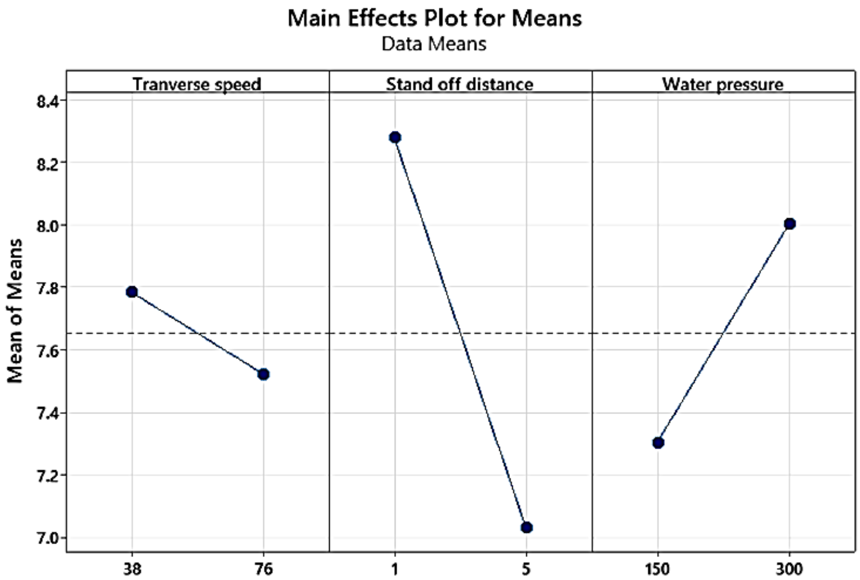
3. Results and DiscussionAnalysis of Taguchi on delamination damage

Table 4 shows an individual and average maximum internal delamination damage measurement for each rank in Taguchi's L8. A combination of Exp. 6 parameters of traverse speed (38 mm/min), stand-off distance (5 mm) and water jet pressure (150 MPa) has the smallest delamination damage radius of 6.25 mm. On the other hand, Exp. 8 parameters of traverse speed (38 mm/min), stand-off height (1 mm) and water jet pressure (300 MPa) have the worst delamination damage radius of 9.35 mm.

Table 4. Delamination radius for all ranks in millimetre

Exp.	1	2	3	4	5	6	7	8	9	10	Ave.
1	10.01	11.41	6.16	8.14	7.47	6.10	6.12	7.37	5.25	6.42	**7.45**
2	7.54	10.45	7.80	10.59	9.64	8.62	8.35	5.14	8.17	7.08	**8.35**
3	7.03	8.60	6.10	8.98	7.24	6.89	6.50	6.62	9.80	4.57	**7.24**
4	5.99	5.56	5.25	4.82	6.92	8.81	8.50	5.33	6.38	7.30	**6.49**
5	7.11	5.99	4.75	4.05	11.14	9.36	4.64	10.70	6.15	12.92	**7.69**
6	8.25	5.14	6.00	7.07	4.72	6.05	4.76	5.87	8.06	6.57	**6.25**
7	7.13	6.00	9.33	5.87	4.19	9.21	11.57	9.13	9.11	7.12	**7.87**
8	5.15	10.85	9.29	7.24	12.25	10.48	9.52	8.85	10.88	9.14	**9.35**

Figure 5 shows the main effects plot for means and signal-to-noise ratios of Taguchi on the composite internal layer delamination. The results conclude that the stand-off distance or the height distance from a composite's surface up to the nozzle's tip has the most significant impact, followed by the water pressure and traverse speed of cutting have the least impact on the delamination issue. Response table for Signal to Noise Ratios is shown in Table 5.



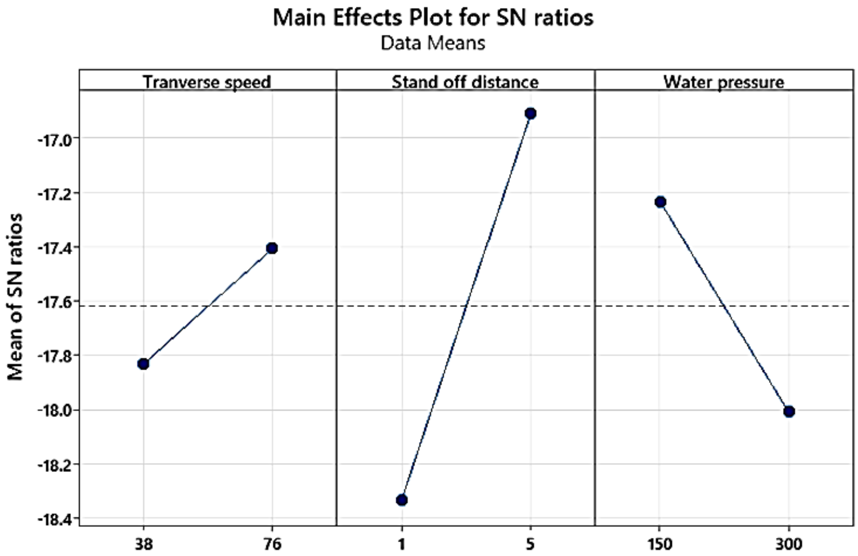


Fig. 5. The main effects plot for (a) means and (b) signal-to-noise (S/N ratios).

Table 5. Response table for signal to noise ratios (Smaller is better)

Level	Traverse speed	Stand-off distance	Water pressure
1	-17.83	-18.33	-17.23
2	-17.41	-16.91	-18.01
Delta	0.43	1.42	0.77
Rank	3	1	2

3.2. Impact of standoff distance

The internal layer delamination decreased with the standoff distance increasing, the SOD of 5 mm and 1 mm produced average delamination diameters of 7.0 mm and 8.3 mm, respectively. A higher SOD permits the waterjet stream to expand or diverge while overcoming air resistance. Therefore, it will approach the composite's surface with less and more random energy distribution. Hence, reduces the kinetic energy of the waterjet stream force in piercing down and prevailed over the adhesion strength between layers [12].

According to Prasad and Chaitanya [20], at increased SOD caused waterjet density and abrasive particulates decreased before hitting the work piece surface at lesser impact force. Although the delamination occurred from a combination of different parameters, SOD will be the main factor in waterjet machining to reduce delamination. However, too high SOD will also result in negative impacts to the cutting capability and surface roughness.

3.3. Impact of waterjet pressure

Waterjet or hydraulic pressure showed a moderated impact on the delamination defect average diameters of 7.3 mm and 8.0 mm for pressures at 150 MPa and 300 MPa, respectively. The kinetic energy of water and abrasive particles increased by the hydraulic pressure increases, resulting in higher splitting of fibre layers or delamination in the composite and is in agreement results of other studies [21, 22]. The delamination starts to occur during piercing and increases as the waterjet passes through the fibber's layering as shown in Fig. 6. The higher the waterjet pressure, the further delamination damage sipped through and away from the piercing point.

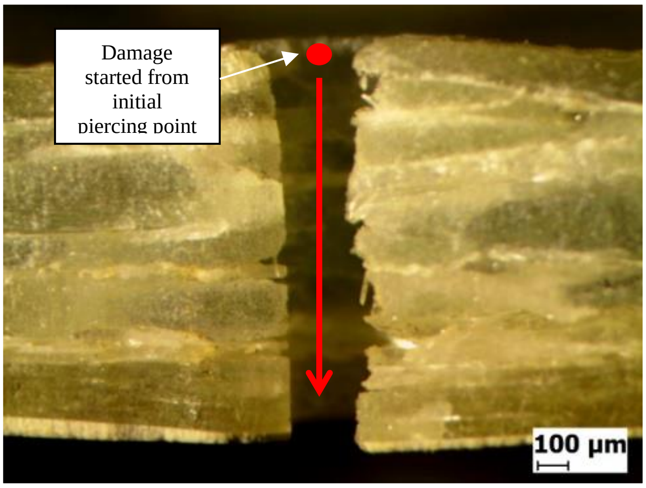


Fig. 6. Delamination damage after piercing.

3.4. Impact of traverse speed

Based on this Taguchi analysis, the traverse speed has the lowest impact on the delamination issue as compared with SOD and waterjet pressure. Average delamination diameters of 7.8 mm and 7.5 mm were observed for 38 mm/min and 76 mm/min, respectively. The results showed that delamination decreases with higher traverse speed. Thus, the duration of waterjet in contact with fibre layers is shorter to cause less damage. During the jet traverse, the force of cutting is exerted more to the side of the fibre layers instead of diagonal force pushing the fibres downward during piercing.

As with the majority of studies, the design of the current study is subject to limitations. Although the Taguchi method has been recognised as a robust statistical analysis tool in process optimization, the outcome of this study showed that the delamination of GFRP cannot be eliminated. This is due to the nature of reinforcement layers are always perpendicular to the direction of waterjet force. Moreover, the L8 orthogonal array of Taguchi is the least number of experiments and requires only 8, further assuming other parameters have negligible impact might be insufficient.

However, in a real manufacturing philosophy, minimizing the cost of optimization study is a very critical and brave decision to be the most economical as long as it meets customer specifications. Another challenge in such a study is how to ensure the consistency of the incoming materials quality and fabrication process, the overall results may slightly differ from time to time. Hence, variations in material and process are unavoidable, but the impacts should be minimized. Further investigation on the reduction of GFRP delamination issue shall be conducted by considering other parameters and tolerances.

4. Conclusions

The experimental work objective was to reduce the impact of abrasive waterjet machining parameters on delamination issues for the 8-layer glass fibre-reinforced polymer composite. A Taguchi's L8 experiment was conducted to optimize selected critical parameters of standoff distance (SOD), traverse speed (TS) and waterjet pressure (WP). The results revealed that SOD contributes the most significant impact to delamination between fibre layers, in which the delamination diameter increases as the standoff distance decreases. At higher SOD, waterjet density with consist of abrasive particulates decreases during the impact. Hence, reduces the waterjet momentum and lower kinetic energy causing less damage. Moreover, the WP has lesser impact as compared with SOD on the delamination damage. Nonetheless a higher waterjet pressure produces more damage and is in agreement with the observation on SOD.

The results also shown that a delamination starts at the instance of piercing and worsens as the waterjet cuts through the fibre layers. The piercing plays major impact on delamination and if possible, to control from low to high waterjet pressure during piercing and cutting, respectively for minimum delamination damage [11] Finally, the TS has the least impact on delamination and less delamination was observed at higher speed. The optimised parameters combination of traverse speed of 38 mm/min, standoff distance of 5 mm and water jet pressure of 150 MPa has the least delamination damage diameter of 6.25 mm. Although the studied parameters have proven to have a significant impact on the 8-layer GFRP delamination issue and should be considered in a new process setup of different layer configurations as well, the parameters' tolerances are not going to be the same depending on the total thickness of GFRP.

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