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A comparative study on the use of laser beam and abrasive water jet in hole making process of woven laminated GFRP

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Abstract. In the manufacturing process, the designed part will be presented in a drawing with all dimensions normally given within a certain range of tolerances. The tolerance defines the limits of induced deviation for which allowance should be made in the design, and within which actual size is acceptable. In laser and abrasive water jet cutting, dimensional accuracy is one of the important parameters to define the quality of produced part. The aim of the present work is to compare experimentally the influence of cutting parameters on dimensional accuracy and strength of hole making in GFRP by using (LBM) and (AWJM) cutting technologies. Full factorial design was used as a statistical method to study the effects of control parameters on the response variables. The results show that abrasive water jet cutting gives a less out of roundness in cutting hole diameter, less reduction in strength and large difference between upper and lower diameter compared to the laser cutting technology of hole making in the type of the GFRP composite material used in the present work.

Nomenclature

LBM	Laser beam machining
AWJM	Abrasive water jet machining
D	nominal hole diameter
t	material thickness
Vc	cutting feed
LP	Laser power
P	water jet pressure
Sod	Stand of distance
O.O.R	out of roundness
Du-DL	Difference between upper and lower diameter
T.S	Tensile strength

Introduction

Glass fiber reinforced polymer (GFRP) composites are used in a large number of industrial applications because of the advantages they have compared to other materials. These advantages are high strength to weight ratio, high modulus, high fracture toughness, and corrosion and thermal resistance. As well as the relative ease of manufacture of components using GFRPs. [1]. As structural materials, joining composite laminates to other metal materials structures could not be avoided [2], and bolt joining efficiency and quality depend critically on the quality of machined holes. Various cutting processes are extensively used for producing riveted and bolted joints during assembly operation of composite laminates with other components. For rivets and bolted joints, damaged-free and precise holes must be made in the components to ensure high joint strength and precision. [3,4]. Conventional machining of hole making in fiber-reinforced composites is difficult due to diverse fiber and matrix properties, fiber orientation, inhomogeneous nature of the material, and the presence of high-volume fraction (volume of fiber over total volume) of hard abrasive fibers in the matrix. Abrasive water jet machining (AWJM) & Laser beam machining (LBM) processes have been used for processing composite materials because of the advantages offered by these technologies as compared to traditional techniques of processing. Laser beam machining (LBM) process has a wide range of applications in different manufacturing processes in industry due to its advantages of high cut quality and cost effectiveness through mass- production rate [5]. LBM is particularly suitable for making accurately placed holes. The material to be cut is locally melted by the focused laser beam. The melt is then blown away with the aid of assist gas, which flow coaxially with the laser beam, in the cutting procedures, different types of assist gases are used such as oxygen and nitrogen. It is suitable for fine cutting of sheet metal at high speed [6]. Abrasive water jet machining (AWJM) has been used also for processing composite materials because of the advantages offered by this technology as compared to traditional techniques of processing. Many researchers carry out the studies on AWJM & LBM of composite materials. Ho-Cheng [7] discussed an analytical approach to study the delamination during drilling by water jet piercing. Their model predicted an optimal water jet pressure for no delamination as a function of hole depth and material parameter. Ramulu et al. [8] reviewed and investigated the AWJ drilling for various materials (steel, aluminum, glass, titanium and polycarbonate). He was found that water pressure, abrasive flow rate and drilling time significantly affected the dimensions and accuracy of the AWJ drilled holes. Hocheng and Sao [9] studied various non-traditional drilling techniques and observed that WJ drilling can be effectively used to make fine holes of medium to large diameter, by contour cutting very speedily. They found that delamination could be eliminated by reducing the jet speed while the piercing capability deteriorates.

This research presents approach to select optimal cutting parameters for high dimensional accuracy and strength, of hole making in laminate GFRP composite by using AWJM and LBM processes. A numerical optimization has been performed using Derringer-Suich multi-criteria decision modeling approach. ANOVA is a basic statistical technique was used for determining the proportion of influence of an input parameter on total variation of response parameters. A set of experiments regarding the two machining technique were conducted, with cutting parameters prefixed on glass fiber reinforced plastic (GFRP) laminate.

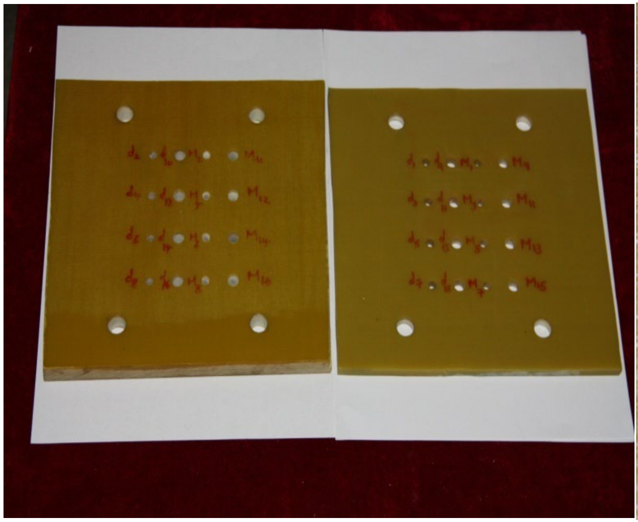
Experimental Work

Cutting Mechanism by LBM and AWJM

Glass fiber reinforced plastic (GFRP) composite materials are the combination of two materials, glass fiber and polymer matrix, that have significant different characteristics. Since each of these materials oxidizes at a different temperature, the laser beam process used to cut the glass fibers would cause the epoxy resin to decompose and melt resulting in a flow of the fibers within the resin and charring and tearing of the resin layer [12]. While abrasive water jet cutting technology uses a jet of high pressure, velocity water and abrasive slurry to cut the target material by means of erosion. It was shown from the scanning electron microscopy (SEM) analysis for the cut surfaces of polymer matrix composites that the erosive process for the matrix material (resin) involves shearing and ploughing as well as intergranular cracking. Shearing or cutting was found to be the dominant process for cutting the fibers in the upper cutting region, but the fibers are mostly pulled out in the lower region of the cutting surface [7].

Material

For the experimental study, a sheet of woven laminated glass fiber reinforced plastic (GFRP), Type 3240 produced by Jinhao Material Co. / China was used as shown in Figs. (1&2). This material is mainly used in aerospace, transportation tools and electrical appliances as insulation materials. The major properties of the laminated GFRP material used are listed in Table 1.



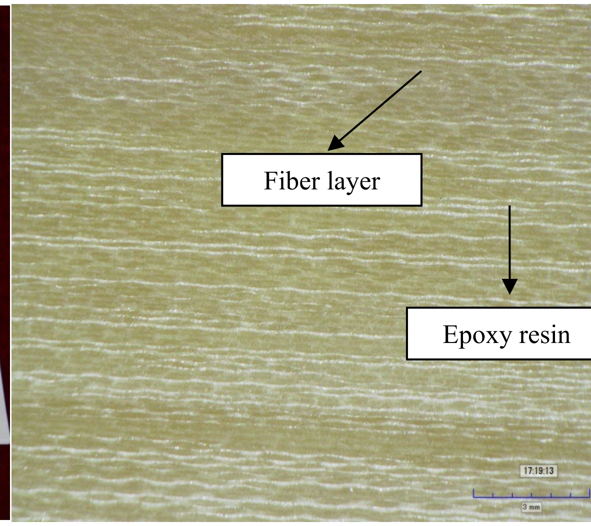


Fig.1 *Laminated GFRP with the two thicknesses.* ***Fig. 2*** *Cross-sectional view.* 3mm

Table 1 *Major properties of Laminated GFRP Type 3240*

	Property	Value/unit
1.	Fiber density	0.82 gm/cm^3
2.	Fiber volume fraction	45%
3.	Max.working temperature	200 ^oC
4.	Tensile strength	295.45 MPa
5.	Layer thickness	0.5 mm

Design of Experiments

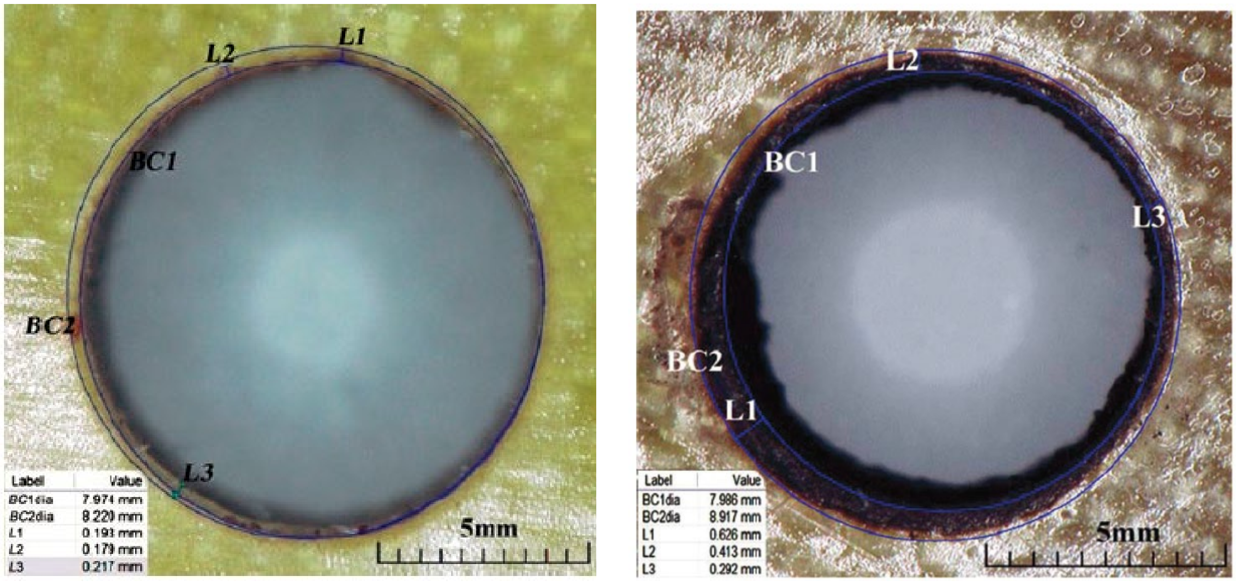
The control parameters are selected based on the available literature, availability of speed and feed rate on the machines, the control parameters ranges are carefully provided between the levels for comparison purpose. A five factors, two-level, full-factorial design of experiments (2^5= 32 tests) was developed for LBM and AWJM cutting process. High and low level of control parameters for AWJM and LBM is shown in tables 2 and 3.

The following is description of response variables (performance measures) to be measured in the tests:

1. Dimensional accuracy in term of out of roundness (O.O.R) as in Eq.1 and the difference between the upper & lower diameter (Du-DL) Fig.3. High out of roundness and high difference between the upper & lower diameter represent low dimensional accuracy.

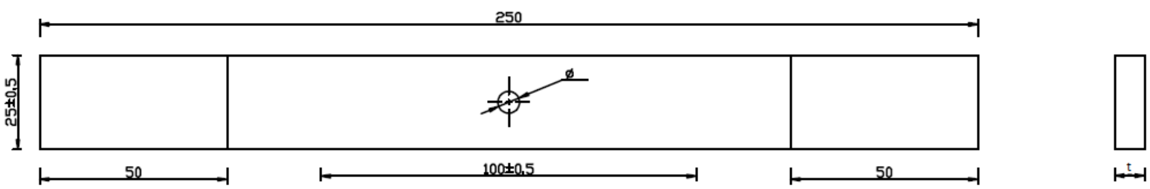
   $$O.O.R = L_1+L_2+L_3 / 3 \quad (1)$$

   Where:
   L_1, L_2 and L_3 is the deviation distance at three different points measured from the optical microscope picture for each hole in the two types of cutting technologies as shown in fig.3.
2. Tensile strength, measured in MPa. 32 tensile test of hole specimens (16 holes cut each by AWJM and LBM) according to ASTM D5766 [13] was carried using Universal Tensile Testing Machine, Type WDW-300, made by Changchun Kexin Com. / China. Fig.4.shows this setup.

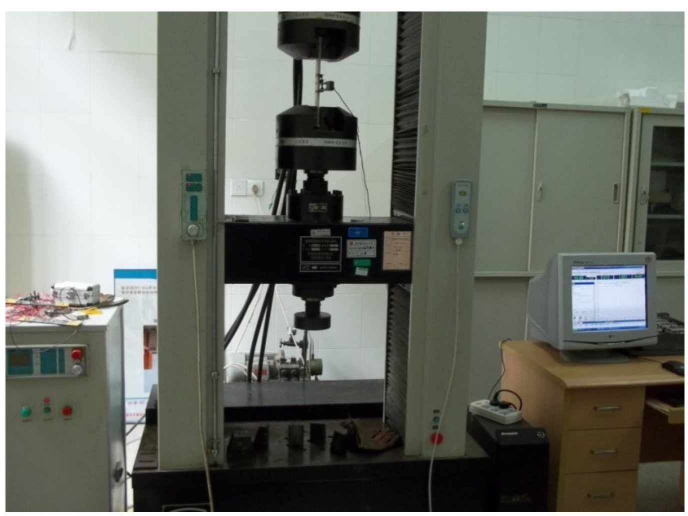


a b

Fig.3 *Optical microscope picture for cutting hole by a: AWJM, b: LBM showing L_1, L_2 and L_3.*



(a)



(b)

Fig.4 *(a) Standard hole specimen for tensile test. (b) Universal Tensile Testing Machine*

***Table 2.** High and Low setting of control parameters in (AWJM).*

code	Input factor	Unit	Level 1	Level 2
A	Nominal hole diameter (D)	mm	6	8
B	Material thickness (t)	mm	8	16
C	Cutting feed (Vc)	m/min	0.2	0.3
D	Jet pressure (P)	Mpa	150	200
E	Standoff distance (Sod.)	mm	2	3

***Table 3.** High and Low setting of control parameters in (LBM).*

code	Input factor	Unit	Level 1	Level 2
A	Nominal hole diameter (D)	mm	6	8
B	Material thickness (t)	mm	8	16
C	Cutting feed (Vc)	m/min	0.2	0.3
D	Laser power (LP)	Kw	1.5	2
E	Standoff distance (Sod.)	mm	1	2

Experimental Setup

The AWJM experiments was conducted on Ultra – high pressure water cutting machine produced by Nanjing Hezhan Microtechnic.Co. Ltd./China with a maximum jet pressure of 220-230 Mpa, abrasive flow rate 3.7 lit/min,water flow rate 3.5-3.7 lit/hr and type of abrasive is Garnet . In all the tests, the nozzle diameter used was 1-mm. LBM experiments were conducted on Rw – 6015 X cantilevered flight optical path laser cutter produced by Nanjing Nanchuan Laser Equipment Co. Ltd. With laser power 2-4 kW, max.speed 50 m/min, table size 2500/1250mm. In all the laser experiments the nozzle (orifice) diameter used was 1.5 mm. The dimensions of the work piece material to be cut in the two types of cutting process were (200 × 200 × 8) mm and (200 × 200 ×16) mm. Optical Microscope type Leica DVM500, having accuracy 0.001 mm was used to measure the cut profile and hole diameter. The experimental setup is presented in Fig.3

(a) AWJM setup (b) LBM setup

(c) Optical microscope setup

Fig. 3 *Experimental setup.*

Experimental Results

The experimental layout and results for the two types of cutting processes are presented in Tables 4 and 5 respectively.

Table 4. *Experimental results for AWJM*

	Control Variables					Response Variables		
S.N	D (mm) **A**	t (mm) **B**	Vc (m/min) **C**	P MPa **D**	Sod (mm) **E**	O.O.R (mm)	Du-DL (mm)	T.S (Mpa)
1	6	8	0.2	150	2	0.111	-0.133	283.95
2	8	8	0.2	150	2	0.141	-0.265	283.53
3	6	16	0.2	150	2	0.145	-0.021	285.23
4	8	16	0.2	150	2	0.114	+0.097	246.76
5	6	8	0.3	150	2	0.161	+0.164	294.74
6	8	8	0.3	150	2	0.135	+0.174	269.12
7	6	16	0.3	150	2	0.062	+0.133	249.67
8	8	16	0.3	150	2	0.094	+0.13	291.32
9	6	8	0.2	200	2	0.16	+0.277	115.20
10	8	8	0.2	200	2	0.131	+0.305	115.51
11	6	16	0.2	200	2	0.071	+0.142	371.12
12	6	8	0.3	200	2	0.154	+0.069	274.61
13	8	16	0.2	200	2	0.105	+0.143	274.60
14	8	8	0.3	200	2	0.133	+0.316	98.01
15	6	16	0.3	200	2	0.084	+0.086	291.78
16	8	16	0.3	200	2	0.174	+0.474	224.71
17	6	8	0.2	150	3	0.222	+0.225	280.39
18	8	8	0.2	150	3	0.229	+0.309	263.97
19	6	16	0.2	150	3	0.088	+0.086	235.36
20	6	8	0.3	150	3	0.102	+0.234	98.95
21	6	8	0.2	200	3	0.275	+0.286	281.71
22	8	16	0.2	150	3	0.069	+0.015	284.67
23	8	8	0.3	150	3	0.122	+0.269	114.78
24	8	8	0.2	200	3	0.167	+0.378	119.34
25	6	16	0.3	150	3	0.122	+0.385	301.45
26	6	16	0.2	200	3	0.138	+0.288	291.45
27	6	8	0.3	200	3	0.153	+0.343	71.97

28	8	8	0.3	200	3	0.198	+0.389	119.56
29	8	16	0.3	150	3	0.124	+0.074	279.34
30	8	16	0.2	200	3	0.125	+0.216	287.21
31	6	16	0.3	200	3	0.128	+0.479	288.22
32	8	16	0.3	200	3	0.196	+0.237	281.73

Table 5. *Experimental results for LBM.*

	Control Variables					Response Variables		
S.N	D (mm) **A**	t (mm) **B**	Vc (m/min) **C**	LP (kW) **D**	Sod (mm) **E**	O.O.R (mm)	Du-DL (mm)	T.S. (Mpa)
1	6	8	0.1	1.5	1	0.251	-0.158	159.08
2	8	8	0.1	1.5	1	0.163	+0.045	246.99
3	6	16	0.1	1.5	1	0.251	-0.039	160.53
4	8	16	0.1	1.5	1	0.260	-0.206	169.93
5	6	8	0.2	1.5	1	0.166	+0.448	108.42
6	8	8	0.2	1.5	1	0.134	+0.061	104.41
7	6	16	0.2	1.5	1	0.393	+0.001	159.54
8	8	16	0.2	1.5	1	0.303	-0.109	138.27
9	6	8	0.1	2	1	0.188	-0.022	71.51
10	8	8	0.1	2	1	0.092	-0.053	70.37
11	6	16	0.1	2	1	0.081	-0.102	65.89
12	6	8	0.2	2	1	0.19	-0.09	77.11
13	8	16	0.1	2	1	0.290	-0.402	65.73
14	8	8	0.2	2	1	0.136	+0.06	79.26
15	6	16	0.2	2	1	0.110	-0.207	70.07
16	8	16	0.2	2	1	0.393	-0.106	69.69
17	6	8	0.1	1.5	2	0.219	-0.316	88.49
18	8	8	0.1	1.5	2	0.292	-0.053	84.19
19	6	16	0.1	1.5	2	0.21	-0.178	136.51
20	6	8	0.2	1.5	2	0.195	-0.009	262.24
21	6	8	0.1	2	2	0.201	-0.022	68.49
22	8	16	0.1	1.5	2	0.220	-0.156	130.18
23	8	8	0.2	1.5	2	0.25	+0.003	94.56
24	8	8	0.1	2	2	0.093	-0.058	73.75
25	6	16	0.2	1.5	2	0.277	-0.256	172.01
26	6	16	0.1	2	2	0.192	-0.256	62.56
27	6	8	0.2	2	2	0.28	+0.09	75.99
28	8	8	0.2	2	2	0.147	-0.015	78.09
29	8	16	0.2	1.5	2	0.459	-0.022	131.32
30	8	16	0.1	2	2	0.325	-0.363	65.84
31	6	16	0.2	2	2	0.185	-0.032	70.18
32	8	16	0.2	2	2	0.333	-0.048	69.88

Results and discussion

Experimental data have been analyzed using ANOVA (Analysis of Variance) and numerical optimization has been performed using Derringer-Suich multi-criteria decision modeling approach. ANOVA is a basic statistical technique for determining the influence of an input parameter on response parameter(s). In Derringer-Suich, multi-criteria optimization technique different desirability functions are assigned to maximization/minimization the response parameters (variables). Further details can be read from reference [10]. All the statistical analyses, including ANOVA and numerical optimization, were performed using commercial statistical software called Design-Expert®. The detail is presented in upcoming sub-sections.

Analysis of Variance:

Tables 6, 7 present ANOVA performed on the data related to the response variables in hole making by AWJM and LBM. The effects of all the individual input variables have been shown. The effects of all the possible interactions among the input variables were analyzed and only the significant interactions have been shown in the plots. This is to be mentioned, with respect to ANOVA table, that effect of any parameter is considered to be significant if *p-value≤0.05*. F and P values only were included in ANOVA tables. F-value is the ratio between mean square of the input parameter to the mean square of error while, P-value is the probability of a test statistics. The bold numbers of p- values represent the significant parameters and insignificant if otherwise.

Analysis of hole making by AWJM and LBM processes:

Tables 7&8 presents ANOVA performed on data related to response variables for the AWJM & LBM.

Table 6. *ANOVA details for Ra, O.O.R, DU-DL and T.S. and identification of significant input parameters in AWJM process.*

Source	O.O.R		DU-DL		T.S.	
	F-value	P- value	F-value	P- value	F-value	P- value
Model	2.03	0.0863	4.12	0.0038	2.75	0.0263
A- (D)	0.13	0.7208	0.51	0.4871	1.02	0.3282
B- (t)	11.5	**0.0037**	11.07	**0.0043**	17.73	**0.0007**
C- (Vc)	0.45	0.5129	3.07	0.0990	2.24	0.1543
D- (P)	2.48	0.1345	12.41	**0.0028**	3.59	0.0763
E- (Sod)	4.71	**0.0455**	3.89	0.0663	1.33	0.2657
A×B	1.21	0.2875	2.30	0.1492	0.24	0.6295
A×C	2.32	0.1474	0.010	0.9210	0.079	0.7825
A×D	0.052	0.8217	1.40	0.2543	1.29	0.2720
A×E	0.12	0.7340	9.88	**0.0063**	0.65	0.4320
B×C	3.34	0.0863	7.59	**0.0141**	1.61	0.2231
B×D	0.061	0.8080	5.21	**0.0365**	5.69	**0.0297**
B×E	0.81	0.3801	0.21	0.6496	1.63	0.2197
C×D	1.21	0.2875	2.71	0.1195	0.073	0.7906
C×E	0.71	0.4134	0.77	0.3944	3.24	0.0907
D×E	1.29	0.2726	0.86	0.3675	0.88	0.3610

Table 7. *ANOVA details for Ra, O.O.R, DU-DL and T.S. and identification of significant input parameters in LBM process.*

Source	O.O.R		DU-DL		T.S.	
	F-value	P- value	F-value	P- value	F-value	P- value
Model	1.76	0.1371	1.22	0.3498	5.14	0.0012
A- (D)	0.46	0.5088	0.028	0.8689	0.46	0.5081
B- (t)	6.18	**0.0244**	1.72	0.2079	0.052	0.8228
C- (Vc)	1.45	0.2464	3.56	0.0776	0.22	0.6462
D- (LBP)	4.76	**0.0445**	0.40	0.5346	63.54	**0.0001**
E- (Sod)	1.82	0.1962	0.29	0.5991	1.00	0.3333
A×B	9.81	0.0064	2.45	0.1373	0.020	0.8904
A×C	0.19	0.6707	0.52	0.4829	2.02	0.1742
A×D	0.22	0.6457	0.22	0.6490	0.81	0.3814
A×E	5.666×10^{-4}	0.9409	1.72	0.2081	1.32	0.2680
B×C	0.82	0.3777	0.91	0.3551	3.859×10^{-4}	0.9951
B×D	0.028	0.8699	1.42	0.2500	1.85	0.1927
B×E	0.12	0.7345	2.04	0.1720	0.11	0.7428
C×D	0.25	0.6215	1.10	0.3105	0.24	0.6314
C×E	0.060	0.8093	1.79	0.1992	4.62	**0.0472**
D×E	0.19	0.6654	0.091	0.7667	0.80	0.3855

The columns F-value and p-value in table 6, which is show the identification of significant input parameters in AWJM process, suggest that effect of material thickness to be cut and stand of distance are significant upon out of roundness. Whereas the significant factors upon the difference in hole diameter are the thickness of the material, pressure of water jet, interaction between hole diameter and stand of distance, interaction between material thickness and cutting feed and finally the interaction between material thickness and jet pressure. The analysis shows also that the significant factors upon the tensile strength are the material thickness to be cut and the interaction between material thickness and jet pressure. While the columns F-value and p-value in table 7, which is show the identification of significant input parameters in LBM process, suggest that material thickness and laser power are significant factors upon out of roundness. The analysis shows also that the significant factors upon the tensile strength are laser beam power and the interaction between laser beam power and the stand of distance (Sod). The analysis shows that there are no significant factors upon the difference between upper and lower diameter.

Figs. 4, 5 and 6 shows, in graphical form, the effects of influential parameters upon out of roundness, difference between upper and lower diameter and tensile strength respectively in AWJM.

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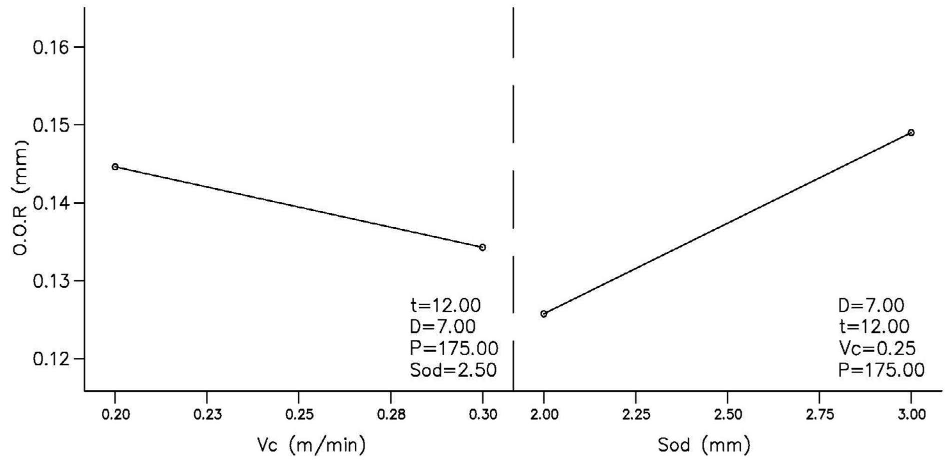
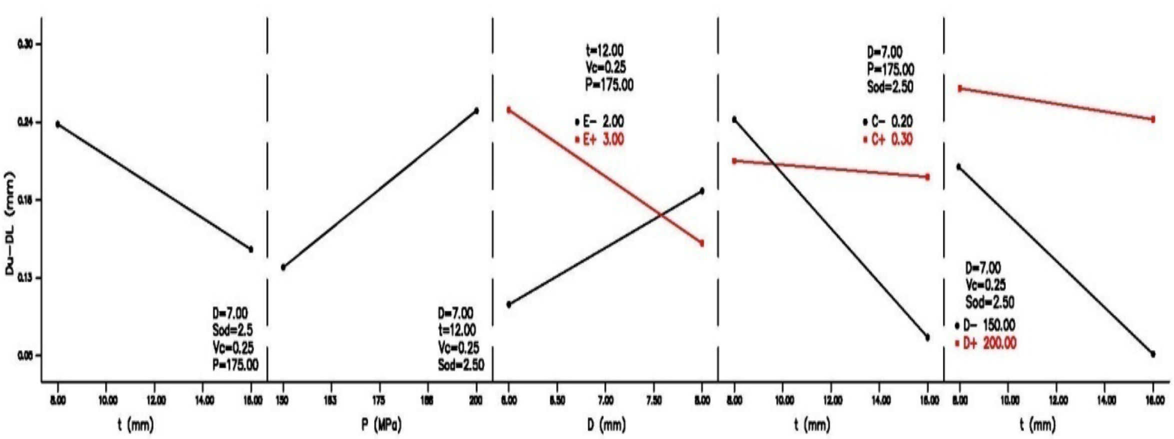


(a) **(b)**

Fig. 4 *Factorial plots showing the effects of (a) cutting feed (b) standoff distance upon out of roundness in AWJM*

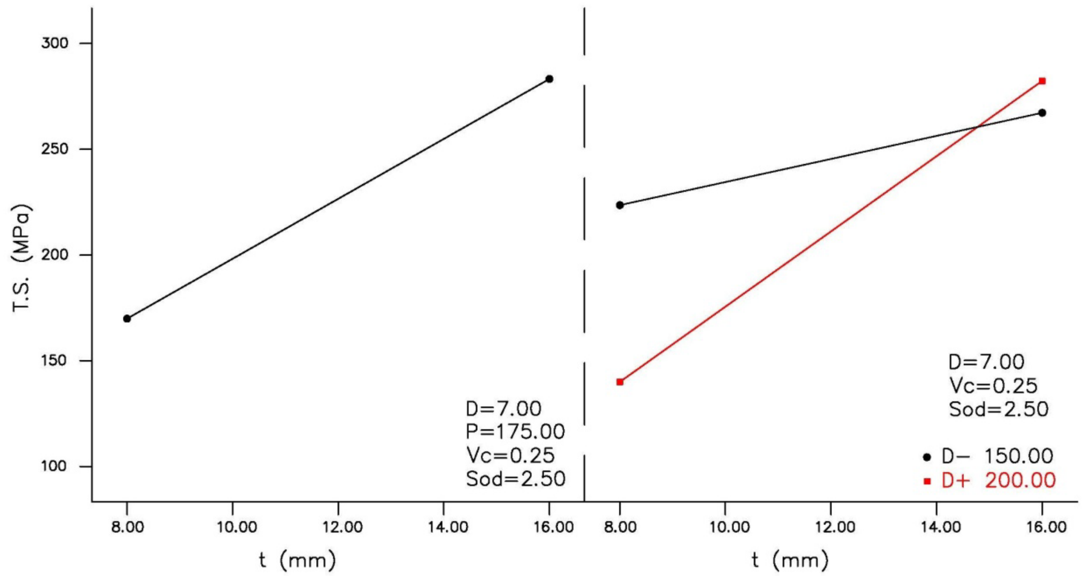
It is clear from graph (a) that as the cutting feed of abrasive water jet increased, the quality characteristic (reducing out of roundness) of the cutting surface will improve. This phenomenon is depending on kinetic energy absorption by work piece due to hydrodynamic friction of abrasive water jet [14]. While graph (b) shows that by increasing the standoff distance the material surface is exposed to the downstream of the jet. At downstream, the jet starts to diverge losing its coherence thereby reducing the effective cutting area that directly affects the kerfs taper angle [13].



(a) **(b)** **(c)** **(d)** **(e)**

Fig. 5 *Factorial plots showing effects of (a) material thickness (b) water jet pressure (c) interaction between nominal hole diameter and standoff distance (d) interaction between material thickness and cutting feed (e) interaction between material thickness and water jet pressure upon difference between upper and lower diameter in AWJM.*

It is clear from graphs (a, b, c, d & e) that the difference between upper and lower diameter is increased as material thickness to be cut decrease and water jet pressure increase this is because, the taper geometry directly depends on the shape of the jet, which is not similar to the shape of a fixed geometry tool. In fact, due to hydrodynamic characteristics of the jet, it is geometry significantly influenced by pressure, cutting feed, standoff distance. Through cutting factors, created tool (water jet) hits the work piece at the upper erosion base, where erosion process begins[14]. When the water jet pressure is increased, the jet kinetic energy increase that leads to a high momentum transfer of the abrasive particles, generating a wider-bottom kerf. leading to a decrease in kerf taper angle[13].

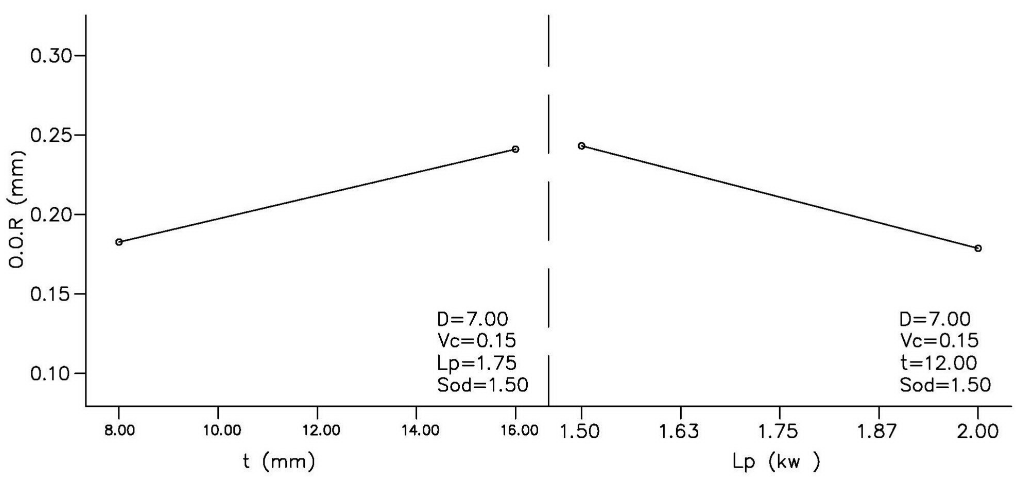


(a) (b)

Fig. 6 *Factorial plots showing effects of (a) material thickness (b) interaction between material thickness and water jet pressure on tensile strength in AWJM.*

It is clear from graph (a) that the thickness of material to be cut and the interaction between material thickness and water jet pressure are affected factors on the strength of the composite. material. Reduction in the strength of the composite is decreased as the thickness of the composite increase. This is related to the formula of calculating the strength of hole specimen which is define as:

Ultimate strength of hole specimen = max.force carried by the test specimen before failure/ gross cross-sectional area (mm^2).



(a) (b)

Fig. *7 Factorial plots showing effects of (a) material thickness (b) laser power upon out of roundness in LBM.*

It is clear from graph (a), that an increase in material thickness for the same laser power, cutting feed and standoff distance results in higher out of roundness (cut path deviation) at the cut region around the hole. This is due to higher input energy required for a larger volume of material removal. While graph (b) shows, that an increase in the laser power with constant cutting feed and a given thickness of material results in lower out of roundness. This is due to the reduction in the cutting duration and the entrance angle with respect to the surface becomes higher. [11].

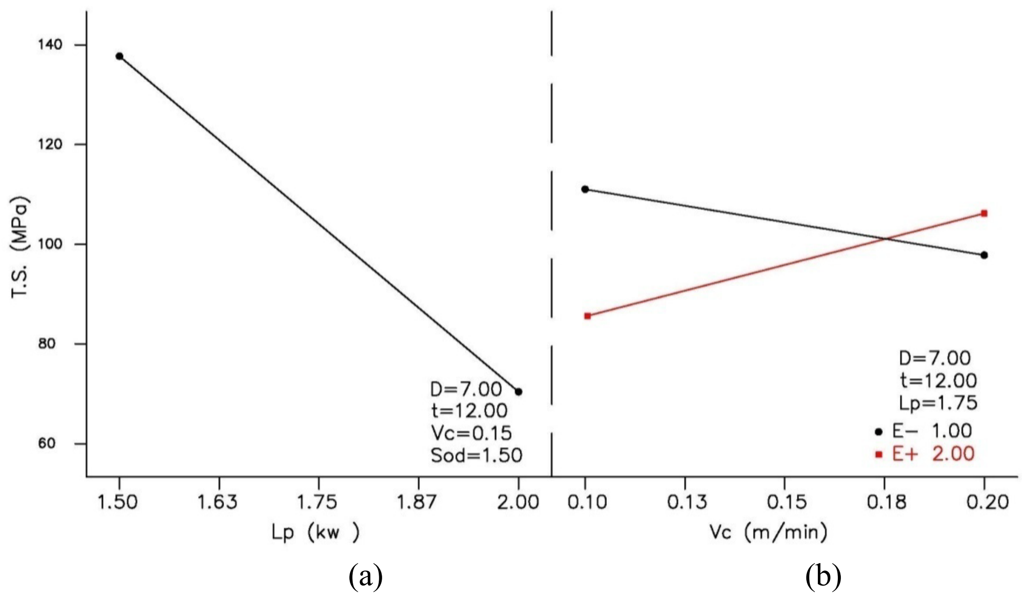


Fig. 8 *Factorial plots showing effects of (a) laser power (b) interaction between cutting feed and standoff distance on tensile strength in LBM.*

It is shown from graph (a) that, the strength of the composite decreases with the increase of laser power. This is because with increasing the laser power, the heat-affected zone (HAZ) is increased and a large volume of fibers in the composite is vaporized, this causes reduction in the strength of the composite. While graph (b) shows less reduction in the strength with increasing the cutting feed. This is because with increasing the cutting feed, the heat-affected zone (HAZ) is decreased [12].

Numerical Optimization

The AWJM and LBM processes have been widely used in industry. The two technologies have procured many overlapping applications and it is thus important for the industry to understand both processes, in order to select the optimum method in different situations. The comprehensive knowledge on dimensional accuracy and strength of hole making in GFRP, would help the users to judge which method is more appropriate for each type of application. The target of numerical optimization in the comparison related to the present study could be any of the following three objectives:

1. Minimize the difference between upper & lower diameter.
2. Minimize out of roundness.
3. Maximize tensile strength (i.e. reducing the reduction in tensile strength)

Table 9. *Recommendations and predictions of multi-objective optimization against each set of objectives and comparison with experimental results in AWJM process.*

	Fixed Parameters		**Optimized Parameters**				
Objectives	t (mm)	D (mm)	Vc (m/min)	P (MPa)	Sod (mm)	Predicted values	Experimental values
Minimize (O.O.R)	12	7	0.3	150	2	0.113mm	0.110mm
Minimize(D_U-D_L)						0.147mm	0.151mm
Maximize (T.S)						275.539MPa	271.614 MPa

Table 10. *Recommendations and predictions of multi-objective optimization against each set of objectives and comparison with experimental results in LBM process*

	Fixed Parameters		**Optimized Parameters**				
Objectives	t (mm)	D (mm)	Vc (m/min)	LP (Kw)	Sod (mm)	Predicted values	Experimental values
Minimize (O.O.R)	12	7	0.1	2	1	0.146mm	0.150mm
Minimize(D_U-D_L)			0.2	1.5	2	0.019mm	0.014mm
Maximize (T.S)			0.1	1.5	1	165.376MPa	168.265 MPa

Tables 9 & 10 presents optimized values (within tested range) of the predictor variables for different objectives in the two cutting technologies. Last column of the table shows the actual results of confirmation experiments performed against each optimized values.

Table 9 shows that minimum out of roundness, minimum difference between upper and lower diameter and maximum tensile strength in AWJM can be achieved by cutting at high settings of cutting feed, low settings of jet pressure and low settings of stand of distance. Table 10 shows that minimum value of out of roundness can be achieved by cutting at low settings of cutting feed, low settings of stand of distance and high settings of laser power. Minimum value of the difference between upper and lower diameter of the cutting hole can be achieved by high setting of cutting feed, high stand of distance and low setting of laser power. Finally, reducing the reduction in strength will be achieved if low setting of cutting feed, laser power and stand of distance is applied.

Conclusions

This work is intended to provide initial technical information relating to the dimensional accuracy and strength of hole making in GFRP by AWJM and LBM. The work presented comprehensive statistical analysis of effects of major AWJM & LBM cutting parameters on out of roundness, difference between upper & lower diameter of the cutting hole, difference between. Thirty-two tests following full factorial design of experiments were performed on the laminated GFRP. The following conclusions can be drawn with regard to the AWJM & LBM of GFRP:

1. In AWJM process, improving dimensional accuracy (reducing out of roundness, difference between upper and lower diameter of the cutting hole) can be done by increasing the cutting feed and reducing the jet pressure and stand of distance.
2. In AWJM process, reducing the reduction in the strength of the cutting material can be achieved by reducing the increasing the thickness of material to be cut and reducing the jet pressure.
3. In LBM process, improving dimensional accuracy (reducing out of roundness) can be done by reducing cutting feed, stand of distance and increasing laser power whereas reducing the difference in the upper & lower diameter of the cutting hole can be done by increasing cutting feed, stand of distance and decreasing laser power.
4. In LBM process, reducing the reduction in the strength of the cutting material can be achieved by reducing the laser power, cutting feed and standoff distance.

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