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Study on abrasive water jet drilling for graphite filled glass/epoxy laminates

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ABSTRACT

This work investigates the effect of Abrasive Water Jet (AWJ) drilling parameters on diameter of the drilled holes in Glass Fiber Reinforced Polymer (GFRP) composite having 2 %, 4 % and 6 % graphite. The experiments were designed using Taguchi L_9 orthogonal array with two replications and the drilling experiments are made using five-axis CNC AWJ machine. The influence of AWJ process parameters such as jet operating pressure, feed rate and Stand-off Distance (SOD) on hole-dimension is investigated and the results are reported. Further, the process parameters are optimized using statistical method. The study shows that jet operating pressure is the most influential operating parameter affecting the hole-diameter on the workpiece and the use of graphite in GFRP composite improve its machinability.

Keywords: AWJ machining; graphite/GFRP laminate; jet pressure; feed rate; stand-off distance.

INTRODUCTION

Mixing of graphite particles with GFRP composite materials improve mechanical and functional properties. Graphite filled GFRP materials are suitable for bearing liners, gears, seals, cams, wheels, brakes, rollers, clutches and bushings, etc. Also, few research studies show that graphite filled GFRP materials are suitable to shield electromagnetic interference in electronic devices [1, 2]. Generally, the products by GFRP are manufactured to near-net shape. However, secondary machining operations are necessary for product finishing and assembly. But, machining of GFRP materials by traditional methods like drilling milling, turning, trimming, etc., is difficult because of the anisotropic, non-homogeneous and abrasive nature of reinforcement. Also, very fine debris developed during machining is hazardous. In addition to this conventional machining create defects such as delamination, fiber pull-out and peel-ups in the material [3-6]. To avoid such defects and make environmentally friendly machining, AWJ machining is found be one of the viable process. Also, the AWJ machined components are free from thermal and mechanical distortion. The dust generated is carried away by the water jet and hazardous chemicals are not used in the process [7]. Hence, from all these favourable AWJ is considered as environmental friendly machining process. Recent developments in material design showing polymer composites are the promising materials in many field of applications. Hence, to study the machinability of polymer composites is also become an attractive area of research. In this direction many researchers have reported the effect of AWJ machining parameters on polymer composites. However, the structure of reinforcement, type of matrix and additives used in fabrication process affects the properties of resulting polymer composites. Hence, it is essential to study the parameters of particular machining for specified composite. From this view in the present work an attempt is made to study experimentally the influence of process parameter on graphite filled glass fabric epoxy composite using AWJ drilling.

From the literature it is reported that the erosion of polymer matrix composite material occurs by shearing, ploughing and inter-granular cracking of the matrix [8]. The process parameters like jet traverse speed, pressure and flow rate of abrasive significantly influence the depth of cut, kerf width and surface taper. The surface quality of the cut-surface depends on jet traverse speed and reported that striations on the surface can be controlled by the oscillation of jet about 2° to 6° along the direction of jet traverse [9]. The jet kinetic energy depends on inlet water pressure and flow rate of abrasive. For cutting of aramid fiber reinforced polymer composites, increase in jet kinetic energy due to increased operating pressure and abrasive flow rate by decreasing the SOD and feed-rate improve the cutting action and reduce the surface roughness as-well-as taper ratio. Higher SOD leads to jet expansion and create surface taper [10, 11]. Such expanded impact of jet generated crack on the work surface which led to water wedging and abrasive embedment resulting in delamination. They also reported Al_2O as abrasives produced slightly lower surface roughness due to higher hardness of abrasive compared to garnet abrasive. Shanmugam et. al [12] developed an empirical model to predict the length of delamination on the graphite epoxy composite. Amar et. al [13], reported a review on solid particle erosion behavior of fiber and particulate filled polymer composite and various erosion models. Further, Alberdi et. al., [14] reported that machinability index model available for metals are not viable for composite materials due to their anisotropic properties.

The latest developments of fluid jet machining from perspectives of system design, modelling of jet plumes and their interactions with the target surface, material integrity and process control, crucial aspects of machine maintenance and safety aspects are presented by Axinte et. al. [15]. Due to complex nature of the process parameters selecting optimum settings is a crucial in AWJ machining. Norfadzlan et al. [16] used artificial bee colony algorithm to optimize the process parameters which produced minimum surface roughness. The performance of algorithm was found to be superior in which the estimated R_a value is 42%, 45%, 2% and 0.9 % lower compared to the values obtained by regression, Artificial Neural Network (ANN), genetic algorithm and simulated annealing methods respectively. Azizah Mohamad et al. [17] adopted a new algorithm called Cuckoo for prediction of the surface roughness which was found to be better compared to other techniques like ANN and support vector machine. Sevil Ergur et al. [18] used an adaptive wavelet network to estimate the cutting speed for machining of titanium work-piece and the effectiveness of this approach is validated with the experimental data. Pavol et al. [19] developed a methodology for on-line adaptations of process parameters to obtain the target surface quality based on the vibrational signals generated by the impact of abrasive particle on the work-piece. Further, Žarko Ćojbašić et al. [20] used ELM (Extreme Learning Machine) to develop a model for estimating the surface roughness. Accuracy of the model is compared with genetic programming and ANN models. The experimental results showed that prediction by ELM model was better compared to the other models.

Generally, the use of harder abrasive particles improves the machining rate, but it lead to abrasive embedment on the cut surface. Although softer soluble abrasives did-not yield higher MRR, F. Boud et al.[21] found that the surface cleaning post-machining removed the embedded abrasives from the cut surface. Deepak et al. [22, 23] optimized the process parameters for delamination-free machining of graphite laced GFRP composite. Since AWJ is the most suitable tool for machining of FRP materials, there is a need to further explore machinability aspects which provide a good database for machine tool manufacturers and the end users for tool offset generation and selection of optimum process parameters. Critical features of the AWJ machining are delamination-free machined surface, kerf taper and surface roughness which depends on settings of the process parameters. With this background, the present work investigates the effect of jet operating pressure, feed rate and SOD on diameter of AWJ drilled hole on graphite filled GFRP composite material and optimize the process parameters for producing minimum deviation from the target hole-dimension.

MATERIALS AND METHODOLOGY

Specimen Preparation

Specimens are fabricated with liquid unmodified epoxy resin Lapox-L12 with hardener- K6, graphite powder of size - 200 µm, bi-directional E-glass fibers (aerial density - 320 g•m^{-2}) as reinforcement. The technical specification of the matrix system is mentioned in Table 1. The material composition of the specimen by weight percentage is resin - 50 %, glass fibers - 50 %. The specimens are prepared with 0, 2 %, 4 % and 6 % of graphite powder in the resin. The matrix is prepared by mixing the resin mixture with graphite powder using magnetic stirrer (Make: REMI, India). Measured quantity of resin and hardener is poured into a glass beaker and stirred for 15 minutes at room temperature. The graphite powder then added to this matrix mixture and stirring is continued for 10 minutes to obtain uniform dispersion of the graphite powder. Fiber fabric of size 250 mm × 250 mm is impregnated with the matrix mixture and layered one above the other. Uniform pressure is applied on the uncured laminate using steel plate to flush out the excess matrix from the mold. Curing is done for 2 hours in compression mode at 140^{0}C and the post curing is done at 180^{0}C for 8 hours in free hanging condition. Figure 1 shows various stages of hand lay-up process adopted in specimen preparation. The final thickness of laminate is 3 ± 0.2 mm.

Figure 1. Specimen preparation by hand lay-up process.

Table 1. Specification of the polymer matrix system.

Technical specification	
Minimum Curing Time	15-30 Mins. at 100 ℃
Pot Life	30 Mins. - 1 hr. at 20 ℃
Viscosity	9000 -12000 MPa. at 25 ℃

Experimental Setup

Figure 2 shows the experimental set-up us used in this work. The machine has five-axis CNC movement with maximum operating pressure up to 450 MPa using the conical nozzle of 0.8 mm diameter. The garnet abrasive particles of size 80 mesh with flow rate of 305 g/min is supplied to the mixing chamber of the cutting head. The impact angle of the jet is maintained at 90° against the work piece.

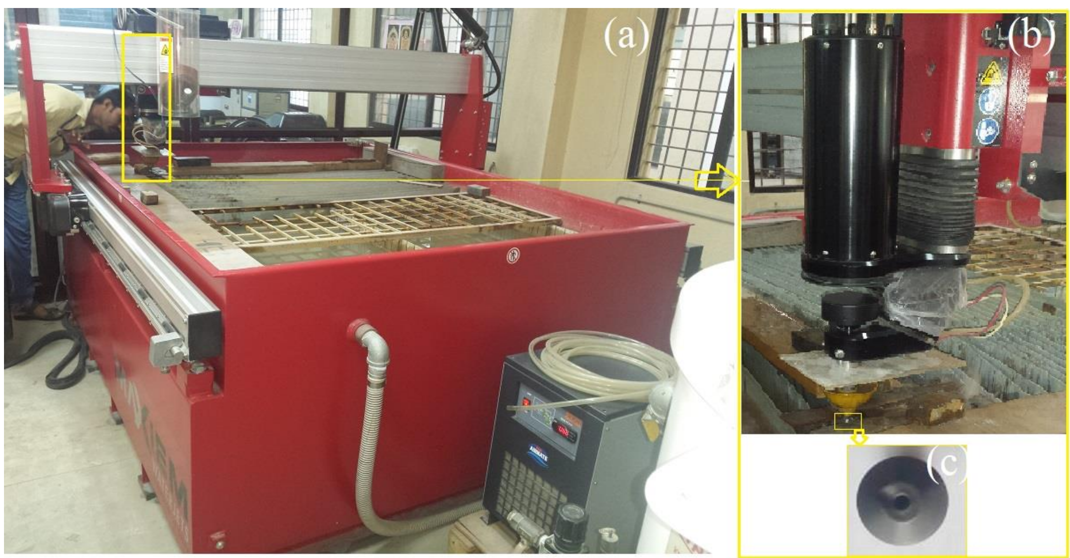

Figure 2. (a) AWJ machine (b) cutting head (c) nozzle.

Experimental methodology

The experiments are carried out by varying the process parameters namely operating pressure, SOD (distance between nozzle tip and workpiece surface) and feed rate. The total degrees-of-freedom (DF) for the study of their main effect is 7 (6 DF for main effects, plus 1 DF for overall mean), hence the nearest standard L^9 (3^3) Taguchi orthogonal array is selected for experimental design. Based on trial experiments the levels of the process parameters are chosen as shown in Table 2. Workpiece is cut into a strips of 25 mm x 250 mm and holes of 4 mm diameter are drilled as per the experimental design shown in Table 3. Figure 3 (a) and 3 (b) shows few drilled laminates with 0 % and 4 % graphite particle lacing. Using high resolution camera (Make: Canon EOS 600D), images of the holes are captured at its top and bottom locations. The images are further processed to determine the physical dimensions of the holes and the results are verified with the measurements made by tool maker's microscope. Table 3 shows the average hole-diameter obtained in each experimental trial. The drilled holes are split vertically and its surface is sputter coated with conductive material for the morphological study using scanning electron microscope (Make: Zeiss EVO 18 with Oxford EDS).

Table 2. AWJ variable process parameters and their levels.

Parameter	Code	Levels		
		1	2	3
Operating pressure (MPa)	A	100	125	150
Standoff distance (mm)	B	1	2	3
Feed rate (mm/min)	C	125	175	225

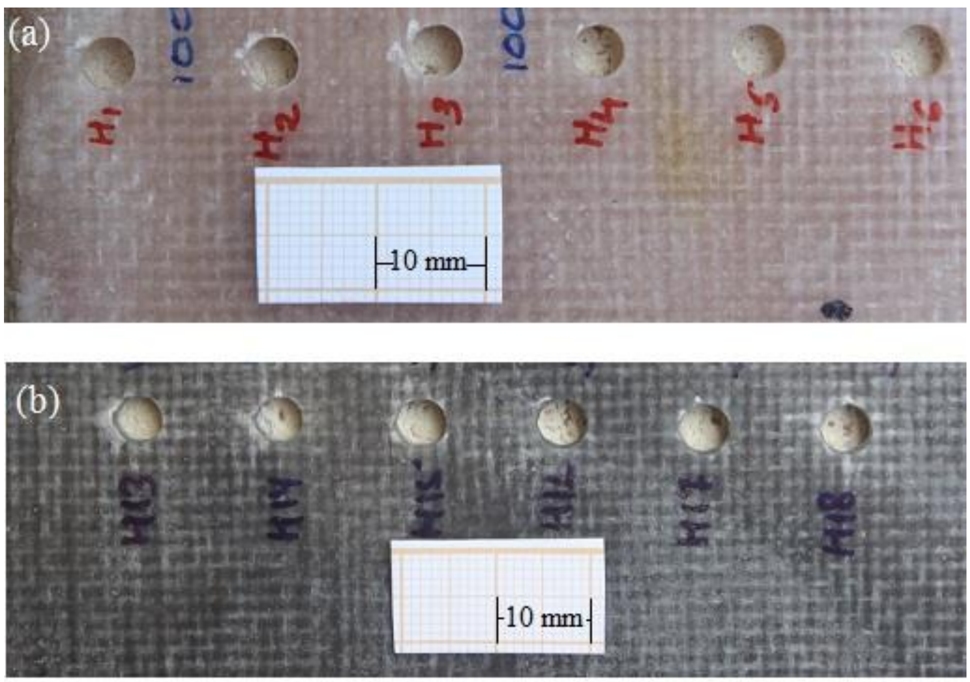

Figure 3. AWJ drilled sample work-piece (a) 0 % graphite (b) 4 % graphite.

Table 3. Experimental design and response data.

Expt.	**Process parameters**			**Hole diameter for different graphite %**			
	Operating pressure	**Standoff distance**	**Feed rate**	**0 %**	**2 %**	**4 %**	**6 %**
1	100	1	125	4.723	4.780	4.837	4.885
2	100	2	175	4.706	4.781	4.839	4.877
3	100	3	225	4.681	4.770	4.827	4.867
4	125	1	175	4.837	4.934	4.993	5.023
5	125	2	225	4.885	4.963	5.023	5.045
6	125	3	125	4.858	4.941	5.000	5.038
7	150	1	225	4.929	4.988	5.048	5.063
8	150	2	125	4.990	5.035	5.095	5.120
9	150	3	175	5.020	5.085	5.120	5.100

RESULTS AND DISCUSSION

Effect of operating parameters

Figure 4 shows the main effect plots of the hole-diameter obtained for work pieces with different composition of graphite particles. It is seen from Figure 4 (a) that the diameter of the hole increased with increase in operating pressure in all the work pieces having different composition of graphite powder. This is due to the fact that the jet kinetic energy increase with increase in jet pressure [24] which lead to production of AWJ with larger diameter, thus resulting in generation of bigger profiles in the drilled holes. For a work piece without graphite, the hole diameter is increased by 5.88 % due to variation in operating pressure from 100 MPa to 150 MPa whereas, the change is 5.42 %, 5.23 % and 4.47 % for the work pieces with 2 %, 4 % and 6 % graphite respectively.

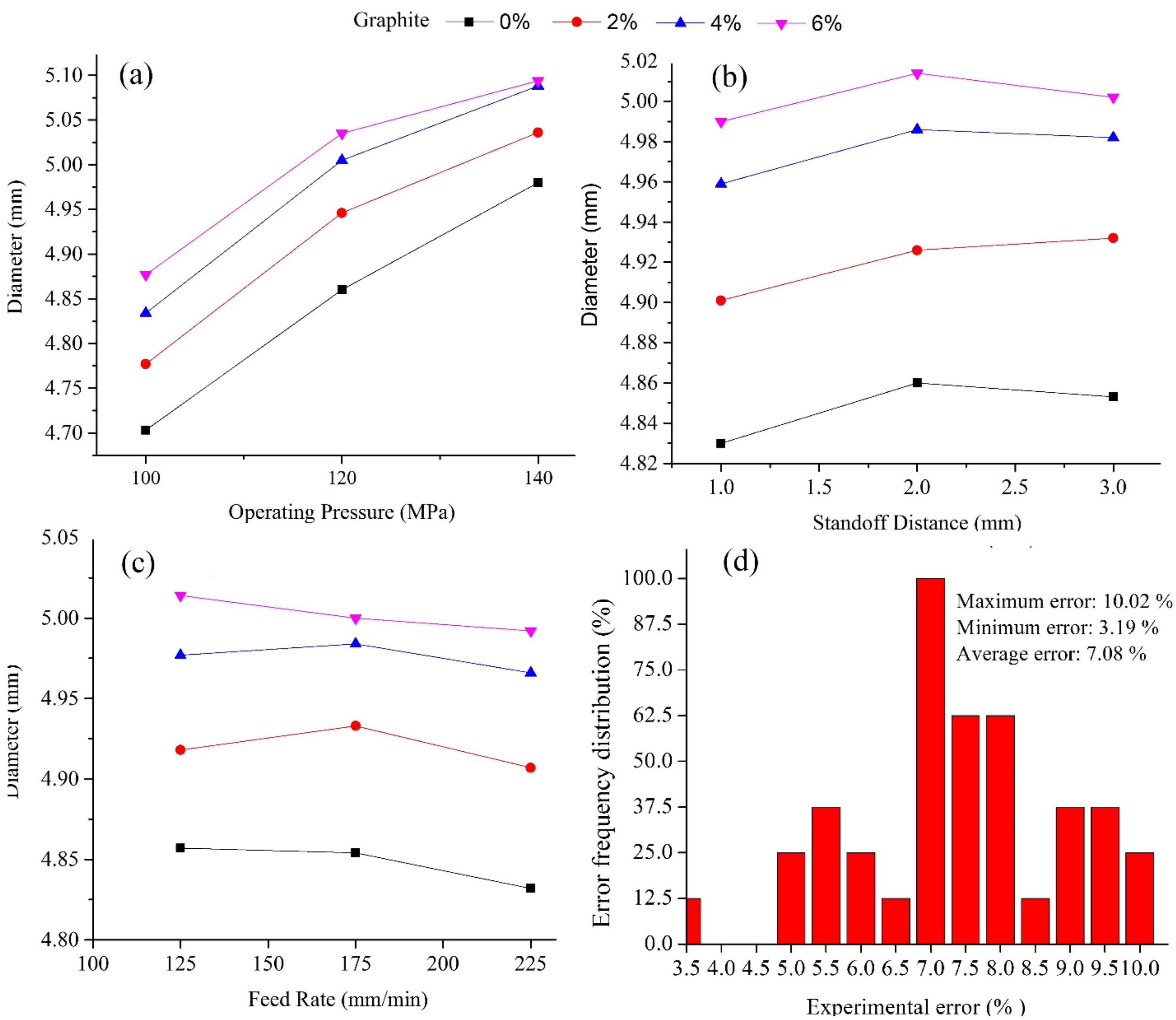

Figure 4. (a) The effect of operating pressure, (b) the effect of standoff distance, (c) the effect of feed rate and (d) experimental error distribution.

The effect of SOD is shown in Figure 4 (b) which shows that, the diameter of the hole increased with increase in the distance of work-piece from the tip of the nozzle. With the increase in SOD, the scattering of the jet occurs due to interaction of jet with surrounding environment. This enlarges the effective cutting area and thus results in enlargement of the hole diameter. For a change in SOD from 1 to 3 mm, the diameter of the hole is increased by 0.47 %, 0.63 %, 0.52 % and 0.48 % for the laminates with 0 %, 2 %, 4 % and 6 % graphite respectively. Figure 4(c) shows the effect of feed rate on hole diameter. It is seen that the diameter of the hole decreased with increase in feed rate. At higher feed rate, the jet impact time on work piece reduces for effective machining. Also, the number of particles which involved in erosion process reduced on the machining area due to increased feed rate. Due to these reasons the diameter of the hole reduced with increase in feed rate. For laminates with different composition of the graphite, the reduction in diameter of the hole observed is 2.5 %, 0.52 %, 0.36 % and 0.45 % respectively. The effect of graphite fillers in GFRP is also observed in figure 4 (a-c). It is seen that increase in graphite content in the work piece increased the diameter of the hole produced. Addition of graphite particles into the matrix acts as a solid lubricant and lowers the coefficient of friction of the resultant composite [25]. Due to this reason, higher the content of graphite, the better the machinability of the composite is observed. The hole diameter is found to be improved by average of 1.49 %, 2.98 % and 3.31 % for addition of graphite by 2 %, 4 % and 6% respectively. Further, the experimental error analysis is carried out to determine the possible experimental discrepancy. By using the replicated values of diameter of the drilled hole, the percentage error distribution is computed and shown in figure 4(d). It may be observed that, the experimental error is normally distributed in the range from 3.19 % - 10.02 % with little right skewness. Standard deviation of the error is 1.49 % and the average experimental error is 7.08 %.

Analysis of variance (ANOVA) for hole diameter

The diameter of the holes thus obtained from different experimental conditions are subjected to ANOVA to find the influence of each process parameter. Table 4 and Table 5 shows the variance of the response data for different work piece with different percentage of graphite filler. The data thus obtained is subjected to Fischer (F) test with 95% confidence level to find its significance. The test revealed that the jet operating pressure has significant influence on the response, but the effect of feed rate and SOD is found to be insignificant.

Table 4. ANOVA (Un-pooled) for GFRP with 0 % and 2 % graphite.

		0 % graphite			2 % graphite		
Source	DF	MS	F	Contribution	MS	F	Contribution
Operating pressure	2	0.05761	31.57	94.80 %	0.05190	41.04	95.17 %
Standoff distance	2	0.00076	0.42	1.25 %	0.00084	0.67	1.55 %
Feed rate	2	0.00058	0.32	0.95 %	0.00052	0.41	0.96 %
Error	2	0.00182		2.99 %	0.00126		2.32 %

*DF-Degree of freedom; MS-Mean square value

Table 5. ANOVA (Un-pooled) for GFRP with 4 % and 6 % graphite.

		4 % graphite			6 % graphite		
Source	DF	MS	F	Contribution	MS	F	Contribution
Operating pressure	2	0.050139	66.09	96.87 %	0.03809	164.90	97.34 %
Standoff distance	2	0.000615	0.81	1.19 %	0.00042	1.83	1.07 %
Feed rate	2	0.000247	0.33	0.48 %	0.00039	1.71	1.00 %
Error	2	0.000759		1.47 %	0.00023		0.59 %

Optimization of process parameters

Table 8 shows the average hole-diameter and delta (Max - Min) values obtained at the different levels of the process parameter for GFRP with 0 %, 2 %, 4 % and 6 % of graphite filler. Based on the delta (Max–Min) values, the process parameters having significant effect on the hole-diameter are ranked as operating pressure I, SOD – II and feed rate – III. Also, it is observed that at process settings: operating pressure (A1) – 100 MPa, SOD (B1) – 1 mm and feed rate (C3) – 225 m/min, minimum deviation from the required hole-diameter (4 mm) is achieved. Hence these settings are the optimum settings which produced holes with minimum deviation from the actual diameter while machining for GFRP laminates with graphite filler up to 6 %. The predicted hole-diameter at optimum settings is 4.66 mm with maximum deviation ± 0.05 mm.

Table 8. Mean hole-diameter obtained at different composition of graphite.

	0 % graphite			2 % graphite		
Level/parameters	A	B	C	A	B	C
1	4.703	4.830	4.857	4.777	4.901	4.918
2	4.860	4.860	4.854	4.946	4.926	4.933
3	4.980	4.853	4.832	5.036	4.932	4.907
(Max–Min)	0.276	0.031	0.025	0.259	0.031	0.026
	4 % graphite			6 % graphite		
1	4.834	4.959	4.977	4.877	4.990	5.014
2	5.005	4.986	4.984	5.035	5.014	5.000
3	5.088	4.982	4.966	5.094	5.002	4.992
(Max–Min)	0.253	0.026	0.018	0.218	0.024	0.023

Study of surface morphology

Figure 5 (a - e) shows the surface morphology of the AWJ drilled hole. It is observed from figure 5 (a - d) that the drilled surface is free from delamination, however the edges of the holes are seen to be damaged (forming fillets) while machining. Figure 5 (b) and 5 (c) shows the craters formed due to the impact of abrasive particles on the cut surface. These craters resemble the river pattern in jet entry region due to the flow of abrasive and water in the form of fine jet.

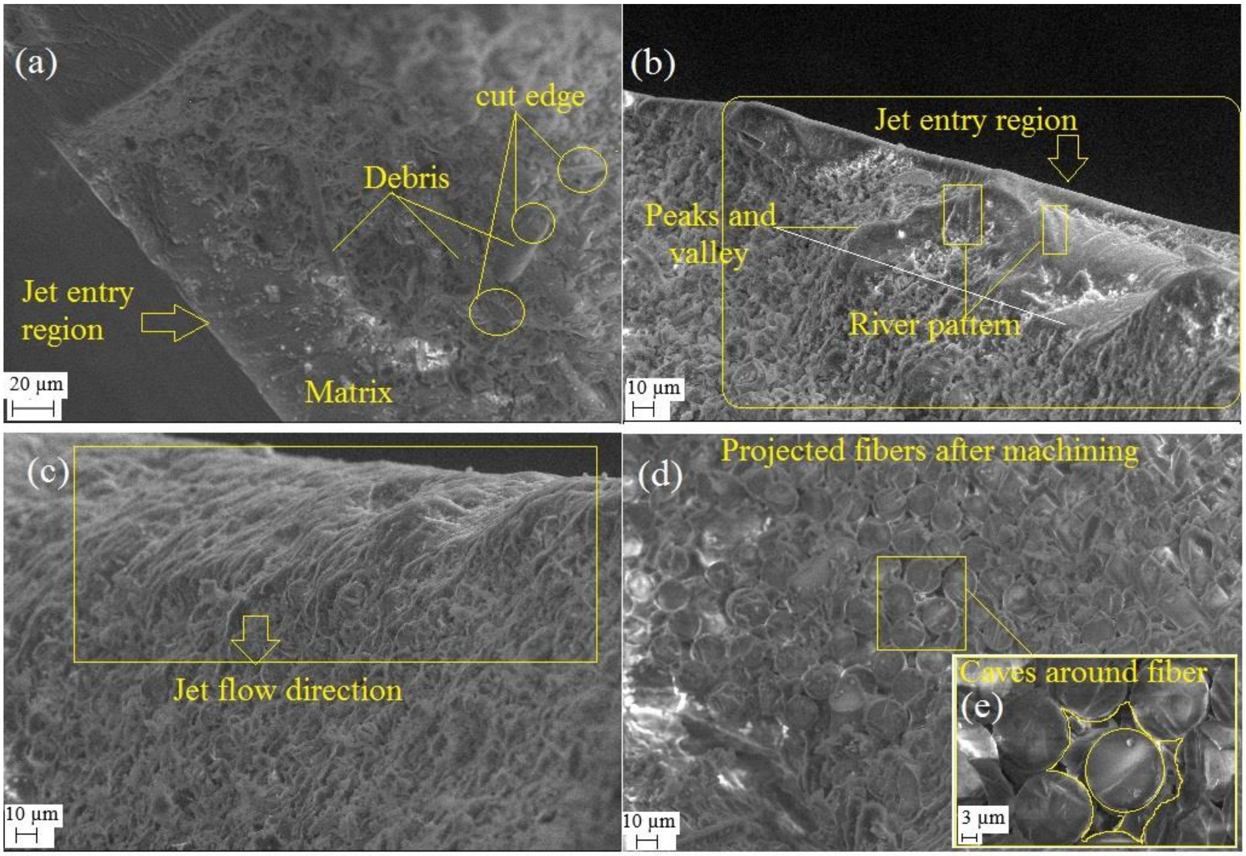

Figure 5. (a) Edge of drilled hole (b) magnified view of jet entry region (c) conical shape formed at jet entry (d) the cut surface at mid-height (e) jet wedging action around the fibers

Although peaks and valleys appears on the cut surface, it is interesting to note that cracks are not formed. This resulted in producing delamination-free surface. However due to the lateral entry of jet into the drilled surface, the matrix surrounding the fibers is seen eroded upto certain depth and leaves behind the projected reinforcement as shown in the figures 5 (d) and 5 (e). Due to the circular motion of the jet in AWJ drilling, the major portion of the fibers are seen chopped at an angle upto 60^0 against the normal chopping of fibers as in case of linear (straight) motion cutting.

CONCLUSION

The following conclusions are drawn from the investigation of AWJ drilling of graphite filled GFRP composite. Addition of graphite improved the machinability and resulted in increase in the hole-dimension upto 2.8 % while drilling of 4 mm hole. Jet operating pressure is the most influential operating parameter which affect the response compared to feed rate and SOD. The optimum settings of the process parameters which produce minimum deviation of hole dimension from the target diameter are operating pressure – 100 MPa, SOD – 1 mm and feed rate – 225 mm/min. The drilled-hole surface is free from delamination, but edges of the holes are seen to be damaged due to the jet impact.

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