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Abrasive Water Jet Machining of Carbon Epoxy Composite

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ABSTRACT

An experimental study of abrasive water jet machining of carbon epoxy composite is presented. Process parameters namely hydraulic pressure, traverse rate, stand-off distance and abrasive mass flow rate are considered for this study. Taguchi approach and analysis of variance are used to study the influence of process parameters on response characteristics including surface roughness and kerf taper. It is found that hydraulic pressure and traverse rate are most significant parameters to control surface roughness and kerf taper. Microscopic features of the machined surfaces are evaluated using scanning electron microscope and compared with sample surfaces machined by conventional method using diamond edge cutter.A set of process parameters is optimised to achieve minimum surface roughness and kerf taper. Confirmation tests are performed to verify the optimum set of process parameters. Defects like delamination, fibre pull out and abrasive embedment are also studied using scanning electron microscope.

Keywords: Abrasive water jet machining, carbon epoxy composite, process parameters, surface roughness, kerf taper, delamination

1. INTRODUCTION

Carbon epoxy composite is an extremely strong and light weight fibre-reinforced polymer (FRP) which contains carbon fibres. It is used in several technological applications including marine, aerospace, sports goods, transportation, infrastructure, etc. It is used to make vessels, corvette, composite masts, propellers, propulsion shafts, etc. in marine industries. Applications of carbon epoxy composite in marine structures offer the potential for significant weight, cost, and signature reductions. But its machining behaviour differs in many aspects from metal machining due to its anisotropic and heterogeneous nature[1].Although conventional machining of carbon epoxy composite is possible using diamond edge cutter, but it results in excessive tool wear, high stresses and temperature, delamination, fibre pull outs, impermissible kerf properties, etc[2]. Abrasive water jet machining (AWJM) process is one of the most recent developed non-traditional machining processes used for machining of composite materials. In AWJM process, machining of work piece material takes place when a high speed water jet mixed with abrasives impinges on it. This process is suitable for heat sensitive materials especially composites because it produces almost no heat and chatter with low stresses[3]. But high surface roughness, improper kerf geometry (Fig. 1) and abrasive embedment are notable difficulties in AWJM.

Some researchers have studied AWJM of composites mainly glass epoxy composite, graphite epoxy composite, natural fibre composite, and ceramic matrix composite through kerf properties such as surface roughness and kerf taper [4-12] and delamination[13,14].

An experimental study of AWJM of carbon epoxy composite to improve kerf properties is presented. The AWJM process is characterised by numerous process parameters but stand-off distance, jet pressure, traverse rate and abrasive mass flow rate are major process variables[3]. Therefore, in the present work these four parameters are considered.

2. EXPERIMENTAL WORK

A flying arm AWJ machine is used for the present study. The machine is equipped with automatic abrasive feeding system along with abrasive metering system. The maximum pump pressure of machine is 260 MPa. The positional and repeat accuracy of the machine is ± 0.04 mm. As the objective of present work is to minimise surface roughness and kerf taper, good quality of garnet abrasives of mesh size # 80 were used for the experiments. Reverse osmosis (RO) water purifier tank is used to supply pure inlet water for machining. The mechanical properties of work piece material are given in Table 1. The thickness of work piece material used in the present work is 22 mm.

3. EXPERIMENTAL DESIGN

The levels of machining parameters namely stand-off distance, jet pressure, traverse rate and abrasive mass flow rate are selected on the basis of literature review[5,9] and available AWJM setup. These levels are given in Table 2. Other machining parameters namely impact angle, nozzle diameter, orifice diameter, and focusing length were kept constant as 90^0, 0.76 mm, 0.25 mm, and 70 mm, respectively. Taguchi's

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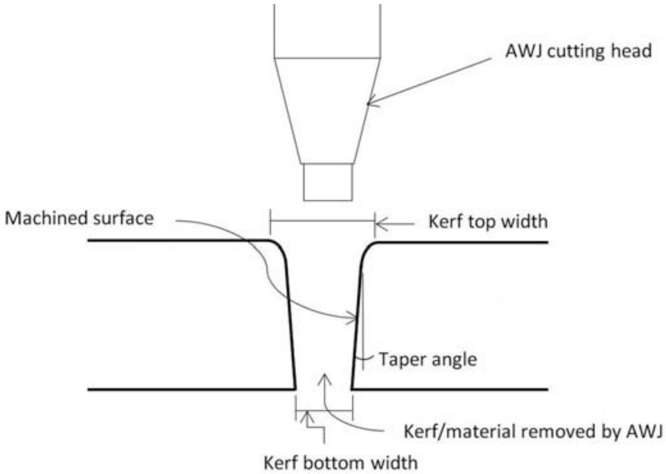


Figure 1. Schematic illustration of kerf geometry.

Table 1. Mechanical properties of carbon epoxy composite material

Property	Value
Volume fraction of carbon fibre by weight	60 %
Density	1.5 g cm^{-3}
Shear modulus - in-plane	30 GPa
Shear strength - in-plane	90 MPa
Compressive strength	570 MPa
Young's modulus	70 GPa
Ultimate compressive strain	0.8 %
Ultimate shear strain - in-plane	1.8 %
Ultimate tensile strain - longitudinal	0.85 %
Ultimate tensile strain - transverse	0.85 %

orthogonal array (L16) is used to plan the experiments. Total 16 work piece samples were machined using AWJM set-up. Thereafter surface roughness and kerf taper of machined samples were measured by using surface roughness tester (Model -Mitutoyo SJ-210) and vision measurement system (Model- Sipcon SDM-TRZ 5300) respectively. The layout of L16 orthogonal array along with measured values of surface roughness and kerf taper are depicted in Table 3.

4. INFLUENCE OF PROCESS PARAMETERS ON SURFACE ROUGHNESS AND KERF TAPER

Influence of process parameters on surface roughness and kerf taper is investigated through analysis of variance (ANOVA) using Minitab 16 software. It is a widely used statistical technique to investigate and model the relationship between response and control factors. Table 4 shows the ANOVA for surface roughness and kerf taper. The analysis is carried out at 95 per cent confidence level.

As depicted in Table 4, the percentage contribution of pressure and traverse rate is around 52.4 and 38.7, respectively. Therefore, pressure is the most significant factor followed by traverse rate. Contributions of other two parameters namely stand-off distance (SOD) and abrasive mass flow rate (AMFR) are insignificant for the response characteristics.

The graphs of responses (i.e. surface roughness and kerf taper) *vs* significant parameters (i.e. pressure and traverse rate) generated by ANOVA are shown in Fig. 2 and Fig. 3.

Figure 2 shows that the surface roughness decreases with increase in pressure and decrease in traverse rate. The reason is that the increase in pressure causes increase in particle velocity at nozzle exit and particle fragmentation inside the nozzle. This fragmentation reduces the size of impacting particle. Also an increase in pump pressure increases AWJ kinetic energy. This increased kinetic energy helps in machining the surface with minimum roughness. With the increase in traverse rate,

Table 2. Machining parameters and their levels

Machining parameter	Level 1	Level 2	Level 3	Level 4
A: Stand-off distance (SOD) (mm)	1	1.5	2	2.5
B: Jet pressure (P) (MPa)	200	220	240	260
C: Traverse rate (TR) (mm/min)	50	100	150	200
D: Abrasive mass flow rate (AMFR) (g/min)	600	700	800	900

Table 3. L16 orthogonal array with response measurements

Expt.	Control factors				Surface roughness	Kerf taper angle
	SOD	P	TR	AMFR		
1.	1.0	200	50	600	3.415	0.750
2.		220	100	700	3.038	0.733
3.		240	150	800	3.036	0.700
4.		260	200	900	3.082	0.633
5.	1.5	200	100	800	3.042	0.950
6.		220	50	900	2.912	0.633
7.		240	200	600	3.083	0.750
8.		260	150	700	2.973	0.733
9.	2.0	200	150	900	3.471	1.133
10.		220	200	800	3.289	1.033
11.		240	50	700	2.515	0.466
12.		260	100	600	2.629	0.500
13.	2.5	200	200	700	3.998	1.350
14.		220	150	600	3.239	1.033
15.		240	100	900	2.763	0.833
16.		260	50	800	2.392	0.433

Table 4. ANOVA table for surface roughness and kerf taper

Source	DOF	Surface roughness			Kerf taper		
		F	P	%P	F	P	%P
SOD	3	1.00	0.501	3.4767	1.56	0.363	4.9408
P	3	15.12	0.026	52.7919	16.52	0.023	52.4559
TR	3	10.59	0.042	36.9592	12.19	0.035	38.7007
AMFR	3	0.94	0.520	3.2807	0.23	0.871	0.7273
Error	3			3.4915			3.1753
Total	15			100			100

DOF- degree of freedom; F- F ratio; P- P value; %P- percentage contribution of respective parameters

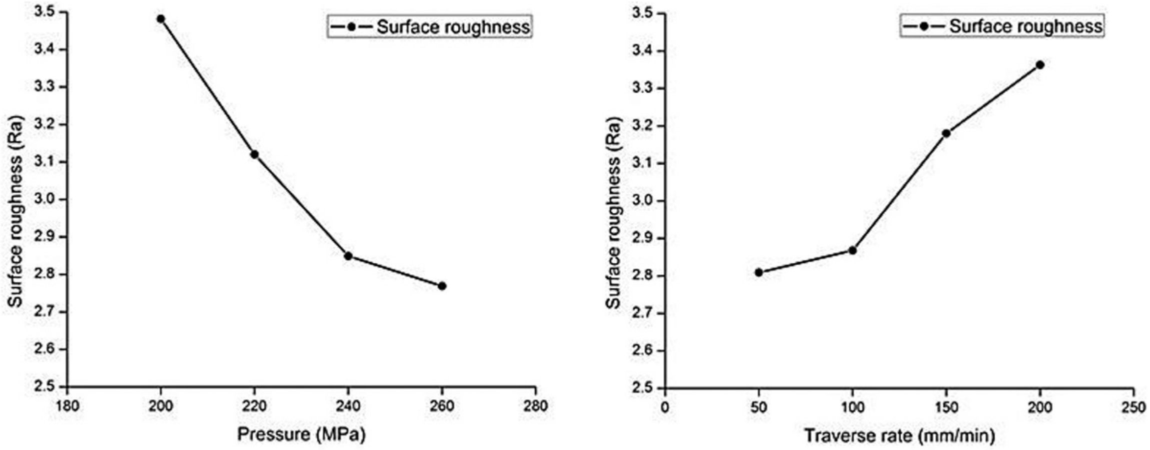


Figure 2. Effect of pressure and traverse rate on surface roughness.

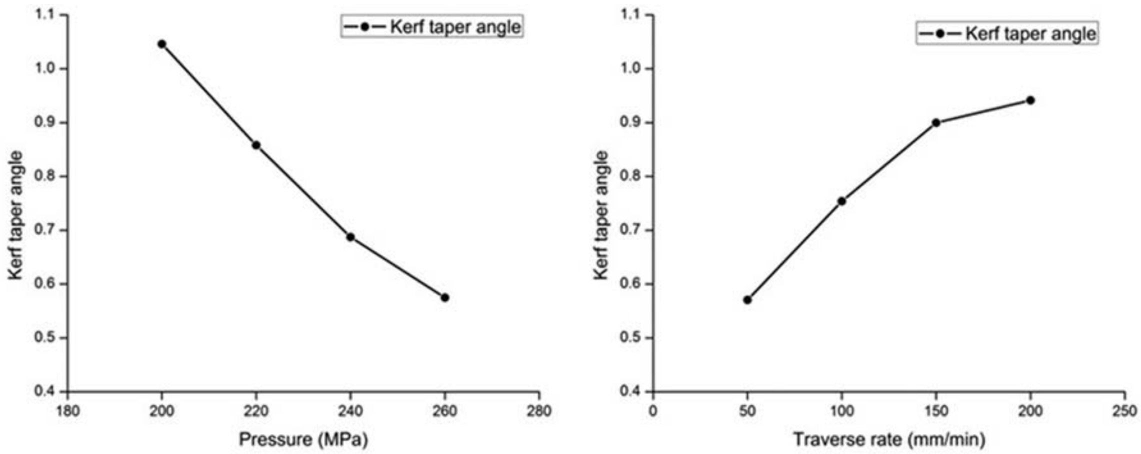


Figure 3. Effect of pressure and traverse rate on kerf taper.

there is less overlapping of machining action and also reduced number of abrasive particles to impinge on surface. It results in increase in surface roughness.

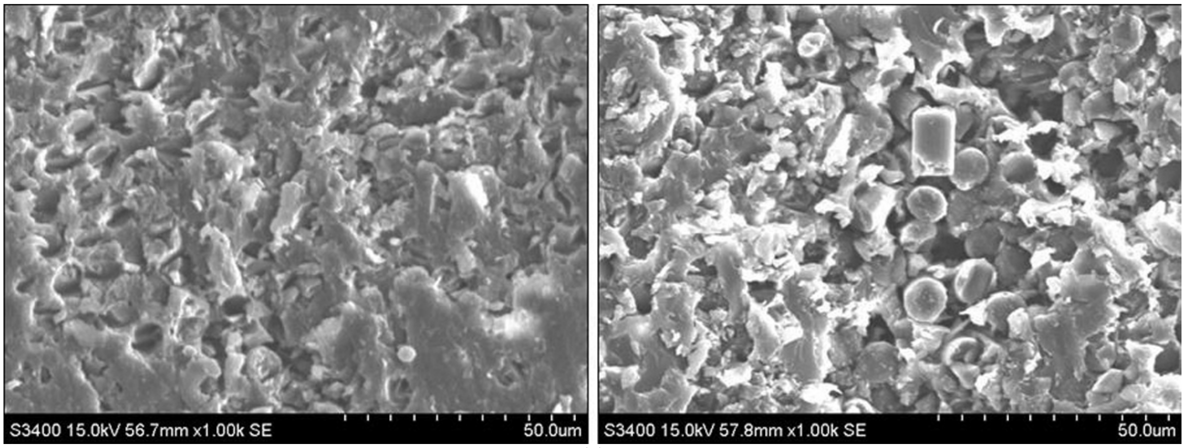
From Fig. 3, it is evident that the kerf taper decreases with increase in pressure and decrease in traverse rate. The increased kinetic energy of jet on increasing pressure cuts the material at bottom region of work piece. This results in surface with minimum taper. The reason of influence of traverse rate on kerf taper is that high traverse rate causes less overlapping of machining action and less abrasive particles to impinge on the work piece surface which reduces the cutting ability of jet. It results in increase in kerf taper angle.

Critical observation of machined surfaces reveal three distinct regions – top (damaged), middle (smooth), and bottom (rough). Two workpiece samples are machined by using the following combination of process parameters -

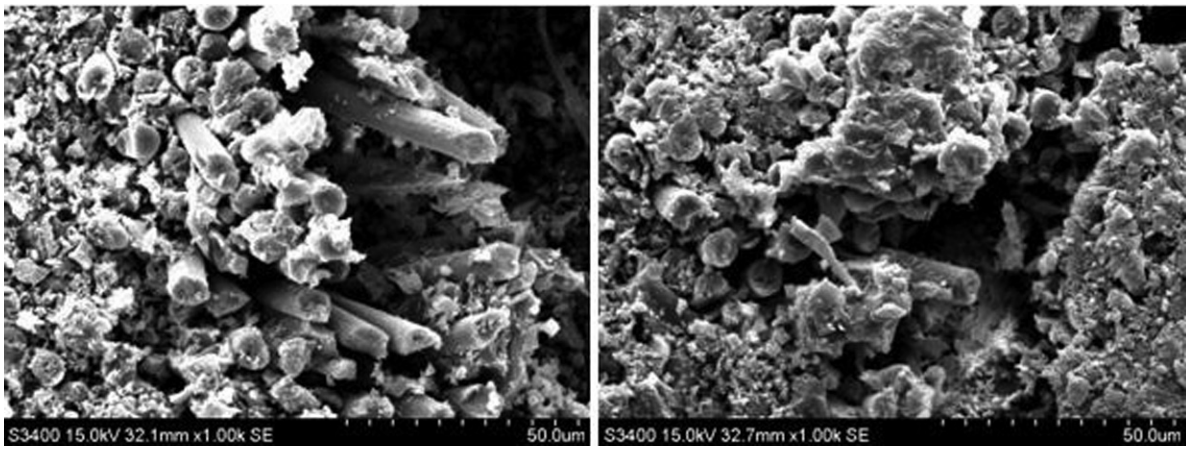
(i) SOD - 2.0 mm, P - 260 MPa, TR – 50 mm/min, AMFR – 800 g/min
(ii) SOD - 2.0 mm, P – 200 MPa, TR – 200 mm/min, AMFR – 800 g/min

These machined samples are examined using scanning electron microscope (SEM) to evaluate the microscopic features. It is observed that fibres are cut smoothly, without fracture and pull-off, and negligible abrasives embedment in the first sample as shown in Fig. 4(a). However, fibres are fractured and pulled off that resulted in rough surface in the second sample as depicted in Fig. 4(a). This is because the jet with low pressure tends to deflect upward after impinging on the workpiece and hence results in fibre fracture with rough surface. Also high traverse rate decreases number of abrasive particles impinging on the surface. In the middle region of both samples smooth surface is observed. However fibre fractures are observed with fibres pull off with some abrasives embedment in the second sample. The low pressure decreases the kinetic energy of jet and reduces its capability of material removal. As a result the surface roughness increases with decrease in jet pressure. Thereafter the surface of bottom region deteriorates due to the jet energy loss during particle impact and jet-material interaction. It is observed that the surface is more deteriorated in the second sample as compared to the first sample. This is due to low kinetic energy of jet in second sample.

For comparison with samples machined by conventional methods, two samples of carbon epoxy composite are machined by diamond edge cutter. Figure 4(b) shows machined sample surfaces. On measuring, it is found that the surface roughness (R_a value) of these surfaces varies from 4.862 to 6.632 which is comparatively higher than that of sample surfaces machined by AWJM. Also it is observed that fibres are fractured with matrix pull out in machining with diamond edge cutter. Damages are observed on entire machined surface of samples



(a)



(b)

Figure 4. Machined surfaces of (a) sample 1 and sample 2, (b) sample 3 and sample 4 (Horizontal surface at 1000x).

in case of diamond edge cutter. However in AWJM, damages occur only at the bottom region of machined surface. Defects produced on machined surfaces are mostly in the form of streaks. These streaks characterise tool trajectory and twisted areas on machined surface. This is due to the cutting face of diamond edge cutter. Tool trajectory plays vital role in course of defects. Also due to matrix and fibre pull out, possiblities of delamination are more in machining with diamond edge cutter. Similar results have been observed by Haddad[10], *et al.*

Figure 5 shows top and bottom kerf quality of AWJ machined samples. Kerf quality varies due to loss in kinetic energy of AWJ. High pressure jet cuts the material through laminates with high kinetic energy but during erosion of material, it also damages surface. This initial damage region spreads on the top edge. Further as machining advances, jet loses its kinetic energy. The loss in kinetic energy results in irregularity of kerf edge at bottom region. Meanwhile rounding of abrasives takes place which reduces cutting ability of jet. In addition, striation occurs at bottom region due to jet with less kinetic energy which finds the path of least resistance.

A set of process parameters is optimised by using ANOVA to minimise surface roughness and kerf taper.

(i) Optimum levels for minimum surface roughness:
SOD-2.0 mm, P-260 MPa, TR-50 mm/min, AMFR 800 g/min

(ii) Optimum levels for minimum kerf taper:

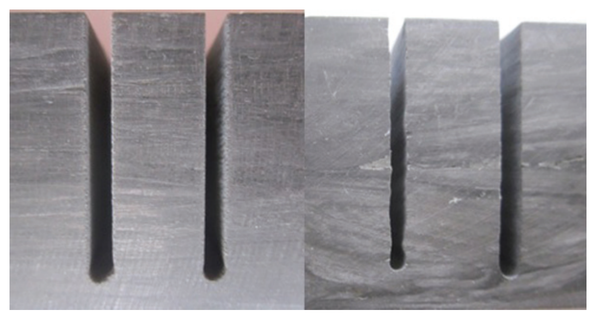


Figure 5. Top and bottom kerf edges.

SOD-1.0 mm, P-260 MPa, TR-50 mm/min, AMFR-600 g/min

The confirmation tests on four samples are carried out using these optimum levels of process parameters. The results of the confirmation tests are given in Table 5. The surface roughness and kerf taper of machined samples are minimal on setting optimum values of process parameters.

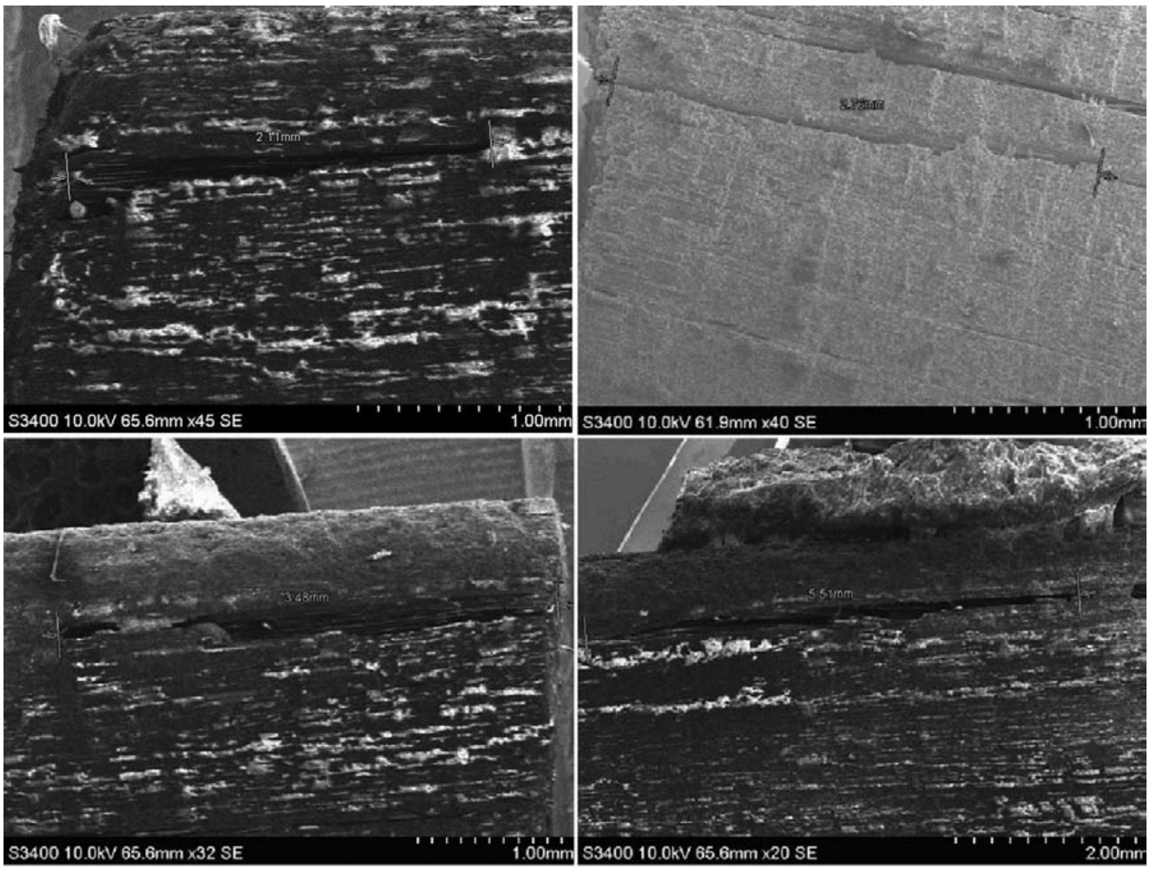
5. DEFECTS IN MACHINED SAMPLES

All the machined samples were observed using SEM to study the defects occurred on the surfaces. Defects like delamination, fibre pull out and abrasive embedment are observed as shown in Figs. 6 (a) and 6 (b). Delamination is a mode of failure for laminated composite materials, in which, repeated cyclic stresses, impact etc. can cause layers to separate

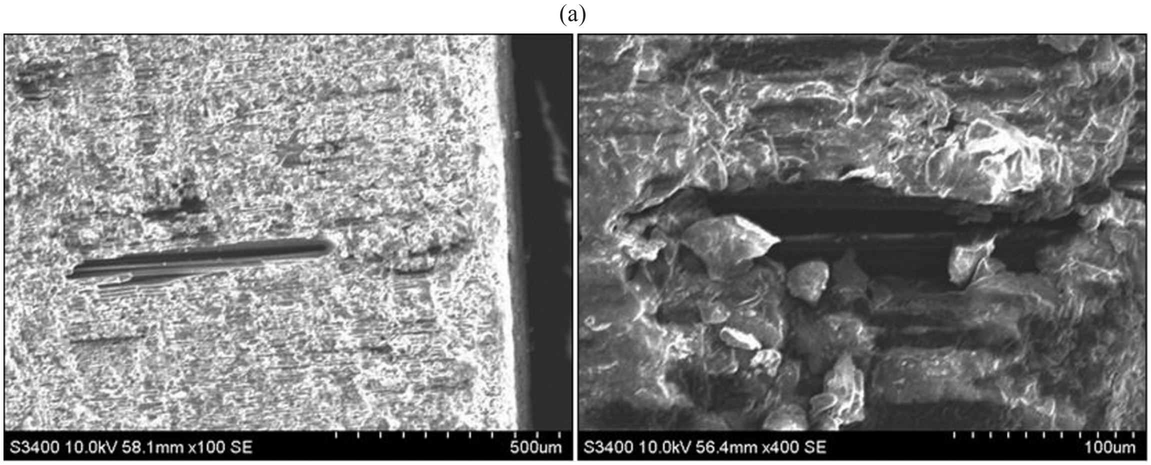
Table 5. Confirmation tests of optimum levels

Sample	Optimum cutting parameters	
	Surface roughness (R_a)	Kerf taper angle
1	2.352	0.413
2	2.374	0.450
3	2.405	0.433
4	2.341	0.410

with significant loss of mechanical toughness. It is observed that delamination generally occurs at the bottom region of machined sample, because the layers at the bottom of the work piece deform elastically and then plastically by jet pressure. In few samples this defect is also observed at top region of work piece. It is due to deflection of jet when it impinges on work piece. It causes lateral flow of jet which penetrates into weak interface between the composite layers and hence results in delamination. The maximum delamination at top region is limited within the region damaged by jet deflection. Shearing action of the abrasive particles plays vital role in erosion mechanism. Therefore delamination is prominent in machined samples cut with low AMFR and high traverse rate as shown in Fig. 6(a). This is because of easy penetration of jet into epoxy resin, but it gets deflected while penetrating into fibre and resin interface. If the interfacial bond is weak, the oncoming crack can experience interface debonding, followed by crack deflection, crack bridging, fiber breakage, and finally fiber



(a)



(b)

Figure 6. (a) Delamination in machined samples and (b) Fibre pull out and abrasive embedment.

pull-out. During AWJM, high directional impact of abrasive particles on workpiece results in fibres pull out as shown in Fig. 6(b). Primary function of abrasives is to cut the material with erosion. But increase in AMFR increases number of abrasive particles impinging on the work piece surface. The excessive abrasives penetrate into the layers of material which result in abrasive embedment. Abrasive embedment is mainly observed at high AMFR and low SOD. At high AMFR, abrasives collide with each other and fail to cut the material. These stray abrasive particles penetrate into the machined surface. At low SOD, abrasives cannot accelerate with high speed water jet which causes abrasives to impinge on material with low kinetic energy. These abrasives penetrate into the layers and machined surface.

6. CONCLUSIONS

Plausible trends of surface roughness and kerf taper with the variation in process parameters have been analysed in the present work. The following conclusions are drawn from the present work.

(i) Hydraulic pressure and traverse rate are most significant parameters to control surface roughness and kerf taper.
(ii) Surface roughness and kerf taper decrease with increase in hydraulic pressure and decrease in traverse rate.
(iii) Delamination defect is prominent in machined samples cut with low abrasive mass flow rate and high traverse rate. Fibres pull out occurs at low pressure and high stand-off distance. Abrasive embedment is mainly observed at high abrasive mass flow rate and low stand-off distance.

A set of process parameters is optimised by using ANOVA to minimise surface roughness and kerf taper. Confirmation tests show that the surface roughness and kerf taper of machined samples are minimal on setting optimum values of process parameters.

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In the current study, his contribution: conducted experiments and analysed the obtained data.

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In the current study, his contribution: supervision of experimental work, analysed the observations and microscopic images to conclude the present study.

Mr R.V. Kalmekar received MTech (Material Science & Engineering) from Indian Institute of Technology, Kharagpur, India. Currently working as a Scientist at Naval Materials Research Laboratory, DRDO, Ambernath, India. His area of research interests include: CAD, FEM analysis, friction stir welding and processing technology, residual stress investigation and related fatigue life assessment of welded joints, contour method of residual stress measurement, welding technology and testing of welded joints.
In the current study, his contribution: provided assistance in the experimental work, and concluding the present study.