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Effect of Delamination in Carbon Fibre Reinforced Polymer during Abrasive Water Jet Machining

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Abstract*: Delamination is a type of defect produced while machining composites or layered materials. Due to matrix crack, shear crack and bending crack delamination is caused. Delamination is usually a separation along a plane parallel to the surface as in the separation of a coating from a substrate or layers of coating from each other. The aim of this project is to explore the study of delamination in carbon Fibre/epoxy composites under abrasive water jet machining. An experimental investigation was held to study the effect of delamination due to abrasive water jet machining on carbon fibre reinforced polymer. Effect of various parameters such as transverse speed, standoff distance, abrasive mass flow rate and water pressure was analysed. Taguchi method was used for overall analysis of parameters. Effect of Kerf width in CFRP material and on fibre cut was analysed step by step. Further observation was done on scanning electron microscopes. It can affect the compression strength of composite laminate and it will slowly cause the composite to experience failure through the buckling. Here the composite of Carbon Fibre Reinforced Polymer is made using carbon fibers and epoxy resin. Further cutting of CFRP is done using Abrasive water jet machining and analysis of delamination at various phases of the material is done. Analysis is done at which parameters delamination is reduced to minimum.

***Keywords*: Abrasive Water Jet Machining, Carbon Fibre Reinforced Polymer, Delamination, Kerf Geometry.**

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I. INTRODUCTION

Composite materials are used in various different types of technological applications such as transportation, construction, infrastructure, aerospace, equipment manufacturing, etc. Reasons which it is used mainly are high strength, stiffness,corrosion resistance and impact absorbing properties. Carbon fibre reinforced polymer(CFRP) is one of the important composite which is a stronger and light weight polymer. The machining of CFRP on the other hand is very difficult because of non-uniform kerf properties, delamination and excessive damage of tool[1]. CFRP consists of carbon fibres which makes it a fibre-reinforced polymer[2]. Main applications of CFRP are marine, aerospace, sports and goods. It is also used in manufacturing of vessels, corvette, propellers, shafts, etc. It is also used for airframe design as it provides high strength structural application with other good mechanical properties[3]. Composites such as CFRP are manufactured using a thermosetting resin which helps the fibres to hold each other. Firstly, the fibres layered and arranged as per required orientation with help of matrix then treated with heat. Then the composite is further machined by non-conventional methods (such as AWJM) as conventional methods would create problems such as tool wear, delamination, temperature rise etc[4]. Quality of composites is improvised by minimizing tool wear and delamination, with increase in production rate[5]. After the composite CFRP is ready for application purpose which is in the form of sheets are to be machined again for their proper dimension of equipment which raises the question which machining method to use and the most appropriate would be abrasive water jet machining[6]. As it provides advantages over conventional machining such as no thermal distortion, high production rates, minimum cutting forces, flexibility etc, it also has disadvantages like kerf taper, poor surface finishing, embedment of particles[7]. But it is better than high stresses, rise in temperature, tool wear, fibre pull outs and unacceptable kerf properties created due to use of conventional machining[8]. AWJM is a flexible machining process because it can be used for different materials such as aluminum, stainless steel, mild steel, composite such as FRP, CFRP ,graphite, epoxy and ceramics such as alumina ceramic,granite,marble etc[9].

In AWJM a high pressure jet of water with an abrasive slurry has an impact on target material causing abrasion and cutting of material. It is an extended version of water jet machining. Abrasives such as silicon carbide and aluminum carbide are used to increase the material removal rate. AWJM is also preferred over laser beam machining (LBM) because of thermal damage while electro discharge machining (EDM) which restricts itself to conducting material. In AWJM every particle helps in the cutting process through erosion and combination of all cutting action of numbers of particles removes material at high rate[10]. This cutting process is used for heat sensitive material that is machined using AWJM.

It is superior to other processes in case of providing contours and flexibility[11]. Now coming to the most important disadvantage of delamination which is critical failure in FRP composites which differentiates from metallic structures[12]. Delamination of a composite occurs in 2 stages. In the first stages separation of the inter-laminar layer caused by the thrust of the jet. Second stage is further proceeding of damage due to delamination by hydro dynamic creation of pressure in inter laminar cracks[13]. It appears because of high intermolecular stresses with low thickness strength. This phenomena occurs due to fibre lying under the plane of laminate doesn't provide proper reinforcement through the thickness so the fibre composite depends on the comparatively weak matrix to hold load in the propagation. This also proves the fact that the matrix resin is very brittle in nature. Delamination occurs also because of intermolecular stresses generation in between of adjacent faces at the interface, it can result in decrease in support on load bearing layers and increasing damage and premature failure. The amount of delamination during AWJM is measured using a moisture uptake procedure changing 6 factors: pressure, stand-off distance, abrasive flow rate, traverse speed, mixing tube size and fibre orientation[14]. This shows a trend in data and prediction of delamination using numerical models. Taguchi method is simple for optimization of parameters in cutting of AWJM. In general case abrasive flow rate, pressure, stand-off distance, traverse rate are important variables etc[15]. These variables are used in order to find the most optimum output and least delamination in the experiment.

II. METHODOLOGY

Carbon Fibre Reinforced Polymer is an extremely lightweight and strong reinforced polymer and also it has good mechanical properties. CFRP is strong and light in weight and can carry a large amount of load so even if it is high in price it is quite widely used and further properties of CFRP depend on what type of epoxy and carbon fibers usd to manufacture. There are many applications of CFRP like in musical instruments, sport equipment, transportation, aerospace, military, marine and many more. Conventional machining techniques like using cutting tools, laser cutting etc. are not feasible in CFRP due to temperature, tool wear etc. Also conventional machining can cause delamination, cracking and fiber pullout.

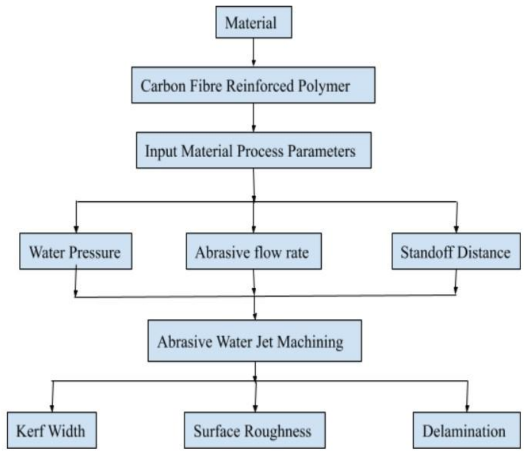

Fig. 1. Methodology Flowchart

Part A

Unidirectional Carbon Fiber Epoxy Polymer was manufactured of size (500*500*20)mm. Figure 2 shows machining of CFRP composite.

Fig. 2. Machining of CFRP Composite

Part B

In order to determine the maximum delamination length during abrasive water jet cutting initially the material (Carbon fibre) was selected and a composite was analysed for delamination. Then the composite plate was cut under the abrasive water jet machine.

Table 1. Parameters for AWJM

Standoff Distance (mm)	Water Pressure	Traverse Speed (mm/min)	Abrasive Mass Flow Rate (gm/min)
1	100	50	150
1	150	100	300
1	200	150	450
1	250	200	600
2	100	100	450
2	150	50	600
2	200	200	150
2	250	150	300
3	100	150	600

3	150	200	450
3	200	50	300
3	250	100	150
4	100	200	300
4	150	150	150
4	200	100	600
4	250	50	450

Above mentioned parameters like Standoff Distance, Water pressure, Traverse Speed and Abrasive Mass Flow Rate were used while cutting specimens. Total thirty two cuts were taken on specimen out of which sixteen were perpendicular to the direction of carbon fibers and sixteen were parallel to the direction of carbon fibers and included 2 seperate specimen. The kerf width was measured under a profile projector. Three readings were taken from individual cut i.e. at top, middle and at the bottom of the cut. Then the average of all cuts was taken. Finally, the kerf width was found.

Table 2. The perpendicular cut to fibres

Entry	Middle	End
Width(mm)	Width(mm)	Width(mm)
1.23	1.27	1.33
1.27	1.25	1.27
1.2	1.21	1.19
1.19	1.26	1.19
1.35	1.32	1.26
1.3	1.47	0.86
1.27	1.23	1.17
1.83	1.25	1.37
1.32	1.4	1.45
1.28	1.44	1.33
1.49	1.3	1.44
1.45	1.33	1.32
1.44	1.48	1.33
1.45	1.34	1.31
1.52	1.54	1.39
1.73	1.23	1.55

Table 3. The parallel cut to fibres

Entry	Middle	End
Width(mm)	Width(mm)	Width(mm)
1.26	0.764	1.37
1.5	1.27	1.31
1.17	1.27	1.23
1.14	1.31	1.17
0.95	1.36	1.31
0.89	1.41	1.33
1.16	1.32	1.24
1.19	1.35	1.37
1.3	1.4	1.49
1.28	1.43	1.32
0.95	1.44	1.66
1.31	1.32	0.5
1.35	1.44	1.35
1.28	1.34	1.4
1.44	0.59	1.47
1.55	1.73	1.6

Table 4. Average Values of perpendicular and parallel

Parallel	Perpendicular
1.131	1.267
1.22	1.2
1.206	1.21
1.206	1.31
1.21	1.21
1.24	1.22
1.30	1.48
1.396	1.39
1.343	1.35
1.35	1.41
1.04	1.36
1.38	1.41
1.34	1.36
1.16	1.48
1.62	1.50

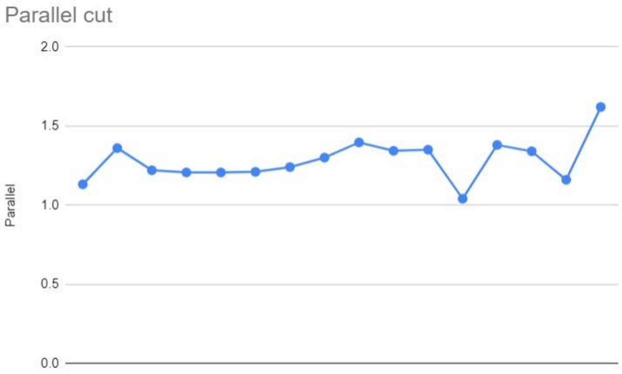

Fig. 3. Kerf width of the parallel cut

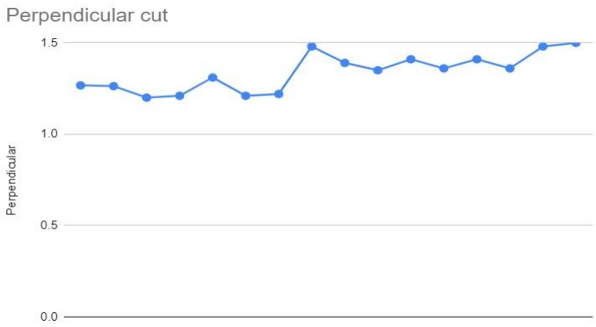

Fig. 4. Kerf Width of the perpendicular cut

Then manufactured carbon fibre was cut using AWJ Machine. AWJM consists of various components like Hydraulic Pump, Compressor, Nozzle, Chiller, Bed, Programmer, Hopper. Power of the motor used in Hydraulic Pump is 50HP. The compressor increases the water pressure from 4 bars to 3000-4000 bars. Then hopper is used to store abrasive material and send it to a nozzle. Chiller is used to lower the temperature of the pump. Programmer installs the program to the AWJM machine. Work-piece for the machining process was placed on bed, its dimensions are 3000mm × 1500mm. Through nozzle, water and abrasive particles impinge on the workpiece. The diameter of the nozzle is 0.7mm and length is 100 mm. CFRP plates with unidirectional fibers are stacked in thickness 20 mm and used as test pieces [15].

Total 32 cuts were taken according to the parameters listed in table no. 1 on a workpiece with sixteen parallel and sixteen perpendicular to fibers. The cut was taken about 30 mm deep inside the workpiece.

Fig. 5. Hydraulic Press

Fig. 6. Mould

Fig. 7. AWJM Machine

Fig. 8. Cutting of CFRP

Table 5. Mechanical properties of CFRP material

Properties	Value
Density	1.54 g cm^3
Shear strength	89 MPa
Modulus of Rigidity	29.5 GPa
Compressive strength	565 MPa
Young's modulus	68 GPa
Ultimate tensile strain—Longitudinal and transverse	0.86%
Ultimate compressive strain	0.82%

III. RESULT

Relationship Between performance parameters and process parameter

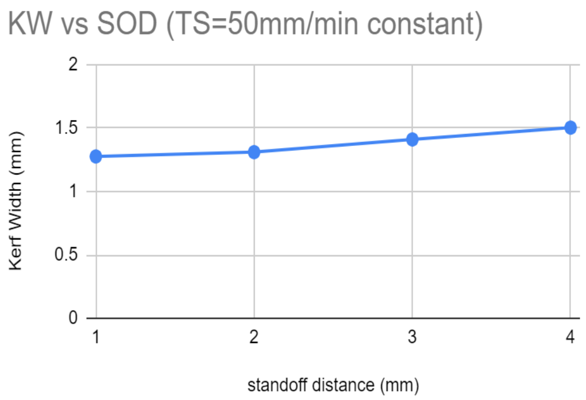

Fig. 9. Kerf width vs SOD (TS=50mm/min constant)

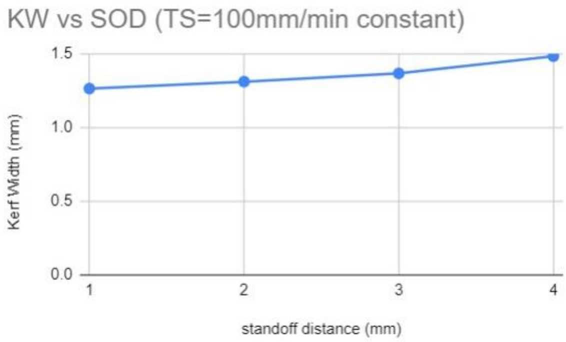

Fig. 10. Kerf width vs SOD (TS=100mm/min constant)

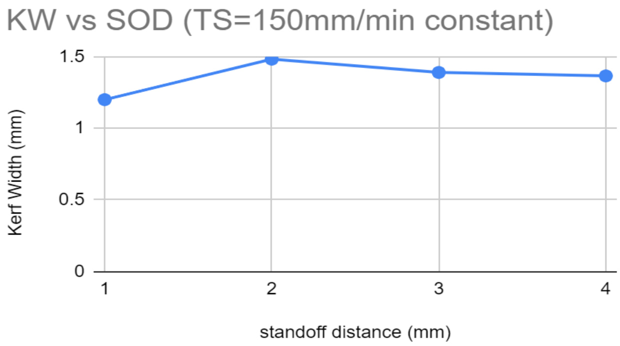

Fig. 11. Kerf width vs SOD (TS=150mm/min constant)

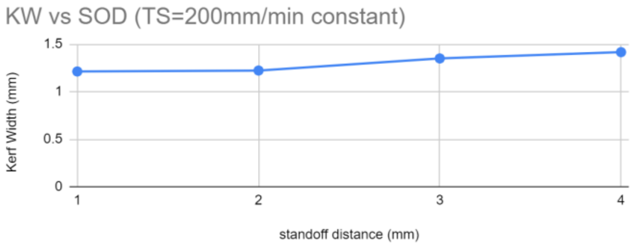

Fig. 12. Kerf width vs SOD (TS=200mm/min constant)

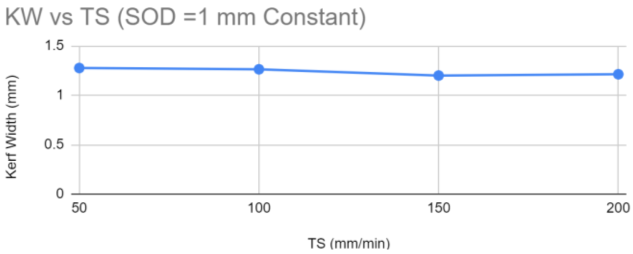

Fig. 13. Kerf width vs TS (SOD =1 mm Constant)

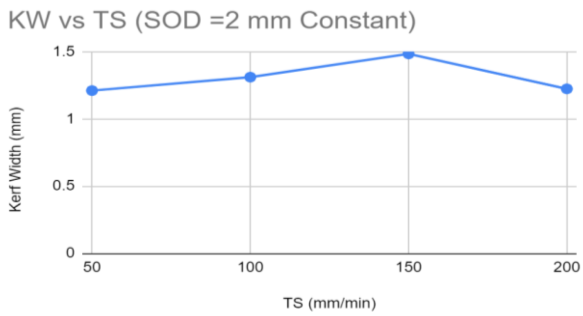

Fig. 14. Kerf width vs TS (SOD =2 mm Constant)

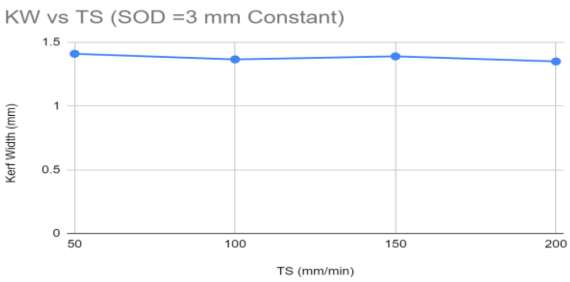

Fig. 15. Kerf width vs TS (SOD =3 mm Constant)

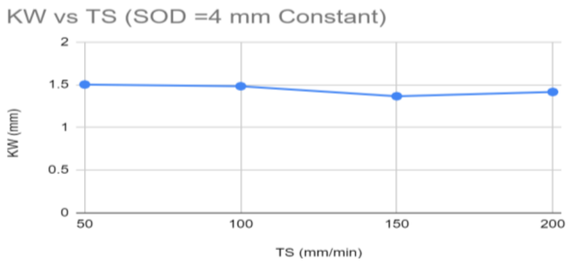

Fig. 16. Kerf width vs TS (SOD =4 mm Constant)

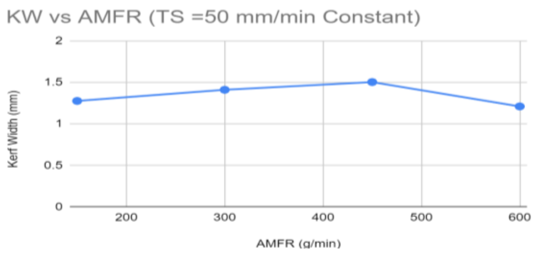

Fig. 17. Kerf width vs AMFR (TS =50 mm/min Constant)

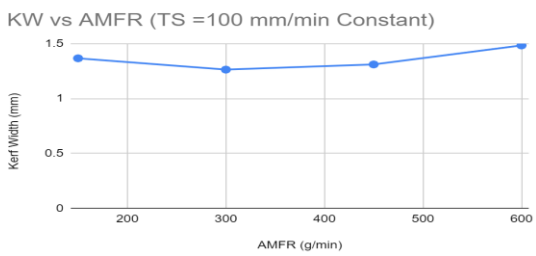

Fig. 18. Kerf width vs AMFR (TS =100 mm/min Constant)

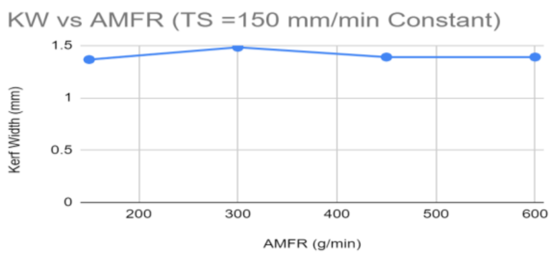

Fig. 19. Kerf width vs AMFR (TS =150 mm/min Constant

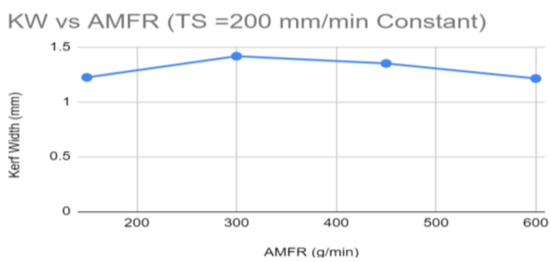

Fig. 20. Kerf width vs AMFR (TS =200 mm/min Constant)

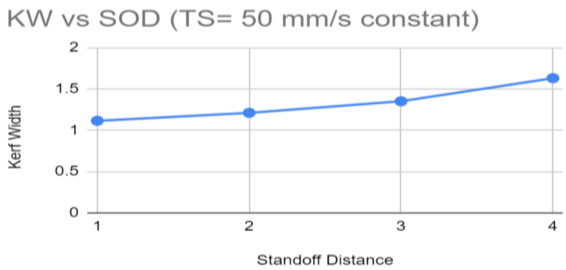

Fig. 21. Kerf width vs SOD (TS =50 mm/min Constant)

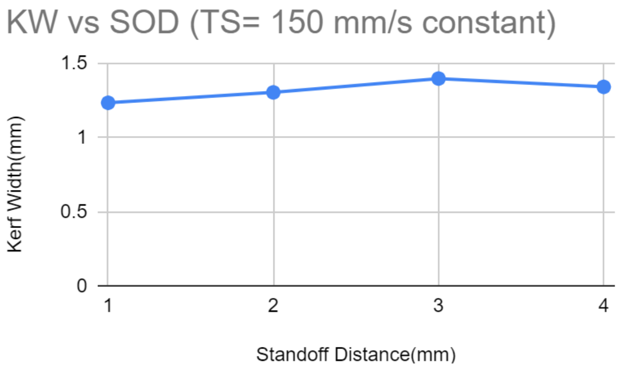

Fig. 22. Kerf width vs SOD (TS =100 mm/min Constant)

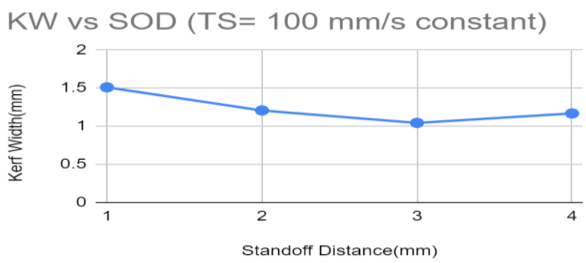

Fig. 23. Kerf width vs SOD (TS =150 mm/min Constant)

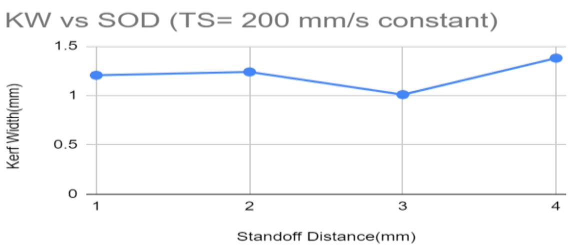

Fig. 24. Kerf width vs SOD (TS =200 mm/min Constant)

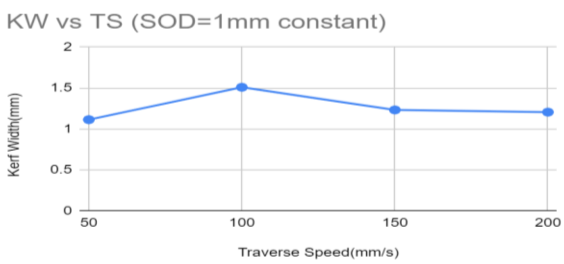

Fig. 25. Kerf width vs TS (SOD=1 mm constant)

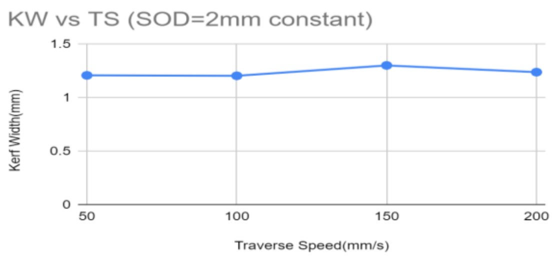

Fig. 26. Fig 26. Kerf width vs TS (SOD=2 mm constant)

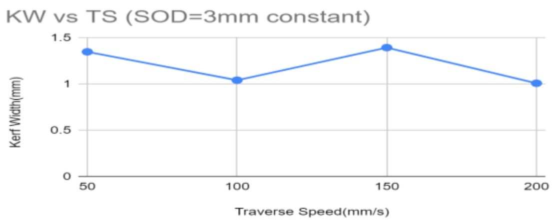

Fig. 27. Kerf width vs TS (SOD=3 mm constant)

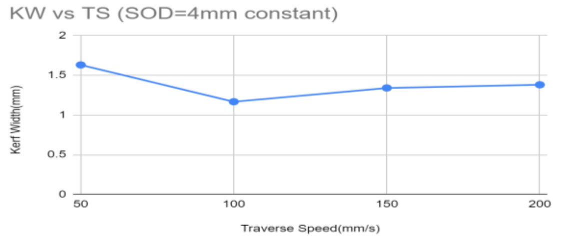

Fig. 28. Kerf width vs TS (SOD=4 mm constant)

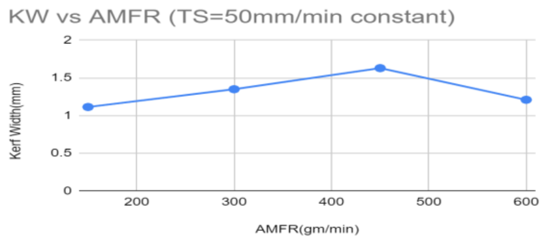

Fig. 29. Kerf width vs AMFR (TS=50 mm/min constant)

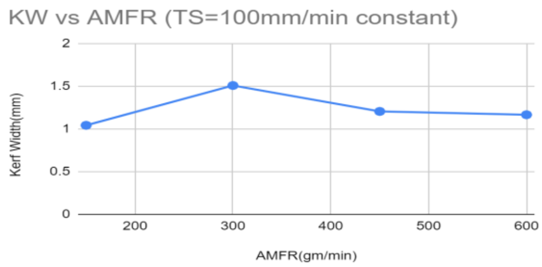

Fig. 30. Kerf width vs AMFR (TS=100 mm/min constant)

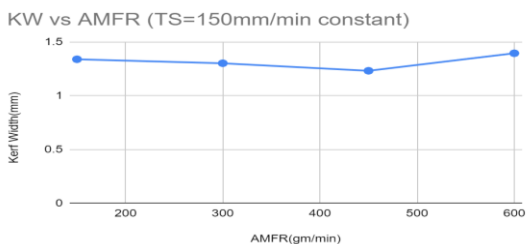

Fig. 31. Kerf width vs AMFR (TS=150 mm/min constant)

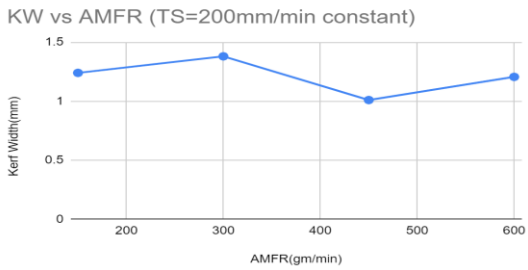

Fig. 32. Kerf width vs AMFR (TS=200 mm/min constant)

From Fig. 9-12. Here, as the stand of distance increases the kerf width also increases at constant transverse speed.
From Fig. 13-16. Here, at a constant stand of distance if traverse speed increases then the kerf width almost remains the same.
From Fig. 17-20. Here, at constant traverse speed, it is hard to find a relation between AFMR and the kerf width. Analysis of Parallel Direction.
From Fig. 21-24. Here, at constant TS, it is hard to find the relation between SOD and KW.
From Fig. 25-28. Here, the kerf width is at maximum 150 traverse speed at constant SOD.
From Fig. 29-32. Here, at constant TS, the kerf width is found at maximum 450 AFMR in some graphs.
Delamination occurs during water jet machining of CFRP. Here the delamination is observed in sample material which has unidirectional fibers. By observation, it can be concluded that delamination occured more at the bottom region of machined sample as it has lack of support. It deformed elastically under jet pressure. Delamination causes weaken interface between the pile of fibers. The crack propogation in the piles is caused by jet deflection at jet entry region.
Delamination is caused due to the stresses which are greater than the required to produce cut in the material. In AWJM abrasive particles also have important role in erosion mechanism. The shearing of abrasive particles causes wedging and during this some abrasive particles get embedded inside the material which is also the main cause of delamination. AWJM penetrates into the epoxy resin easily as compared to fibers and causes sudden variation in jet propagation. This variation in jet penetration rate causes delamination.

Table 6. Result Table

Parameters				Maximum Delamination Length
SOD	P	TR	AMFR	Observed
4	150	150	100	5.58
3	150	200	450	1.70
3	200	100	300	1.01
2	100	100	150	6.97
4	200	100	400	0.713

IV. CONCLUSION

Above results concludes that Delamination occurs due to penetration of abrasive particles and water in the piles of CFRP.

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Further it can be concluded that delamination decreases as Abrasive Mass Flow Rate and Hydraulic pressure increases and delamination increases when Traverse rate is increased. Delamination is mostly seen at end region of machined workpiece in a sample. At some parts fiber pullout is also observed.Kerf width is observed more at perpendicular cut in CFRP as compared to parallel cut.

Probability of finding abrasive particles in sample is more when SOD is less and Abrasive Mass Flow Rate is more.

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