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An Experimental Study on Carbon Fiber Reinforced Plastic by using AWJM

Y. Anantha Reddy[1], P. Rajiv Ranjan Reddy[2], U. Tirupathi[3], V. Jagadish[4], T. Prudhvi[5]
[1]*Assistant Professor, Mechanical Engineering, St. Martin's Engineering College, Secunderabad, Telangana, India*
[2, 3, 4, 5] *Students of Mechanical Engineering Dept. St. Martin's Engineering College, Secunderabad, Telangana, India*

Abstract: Abrasive water jet machining (AWJM) is widely utilized in aerospace, marine and automotive industries for trimming composites. However, it has some challenges when cutting carbon fibre reinforced plastic (CFRP) composites materials such as cut accuracy and quality. More experimental work is required to provide sufficient machinability databases for manufacturing engineers. This paper represents an experimental study and statistical analysis for cutting 2 lay-up configurations of multidirectional CFRP laminates. Different AWJM conditions include jet pressure, feed rate, and standoff distance are experimented using full factorial design of experiments. Machining process responses include top and bottom kerf width, kerf taper, machinability and surface characteristics have been evaluated using analysis of variance (ANOVA) technique. A process cost model for the AWJM is shown.
Keywords: CFRP; Composite; AWJ; Water jet; Cutting; Roughness, Machinability, Model.

I. INTRODUCTION

Carbon fibre reinforced plastic (CFRP) composites are used for light-weighting of structural components of an aircraft which in turn leads to an improved fuel economy; reduced emissions and increased payload of aircrafts. Material behavior under conventional machining is different to homogenous metals and alloys. The non-homogeneity, anisotropy, and high abrasiveness and hardness of the reinforcement fibres make the machining of CFRP a difficult task. Poor machining conditions cause delamination and fibre pull-out that reduce the fatigue strength and adversely influence the long term performance. The abrasive nature of carbon fibres causes rapid tool wear which increases the cutting forces and warmth generation, induces defects and deteriorates the surface integrity. Depending upon the cutting environment, the temperature can soar to exceed 300°C which is higher than the glass transition temperature. There is a growing interest in non-conventional machining techniques in attempt to avoid the shortcomings associated with conventional machining.

II. LITERATURE STUDY

Carbon Fiber reinforced composites offer high strength-weight ratio, high modulus- weight ratio, high fatigue strength-weight ratio, high fatigue damage tolerance, low coefficient of thermal expansion and high internal damping (Mallick 1988). These properties make fiber reinforced composites emerge as the major structural material in the aerospace, vehicle and shipping industry where weight reductions as well as exceptional physical and mechanical properties are of major concern. Although composite materials are manufactured to near net shape, a need often exists for machining operations. Composite materials can be one of the most difficult-to-machine materials due to their inherent inhomogeniety, abrasive nature of reinforcements and anisotropic nature, resulting in high tool wear and sub-surface damage. The first theoretical work on FRP was presented by Everstine & Rogers (1971). They did the theoretical analysis of plane deformation of incompressible composites reinforced by strong parallel fibers. While there exist an immense range of possible combinations in composite materials, it primarily focuses on the discussion on machining of fiber and particulate based composites. Machining of Fiber reinforced composite materials depends on the properties of fibers and matrix and their effects on the machining process.

For instance, M. Saleem and John Montesano compared the fatigue strength of conventionally drilled holes in unidirectional CFRP as opposed to Abrasive Water Jet Machined (AWJM). They later found that less damage accumulation with the endurance limit for AWJM cut laminates of 10 % higher not to mention the poor surface integrity of the conventional drilling. A fundamental variation exists between AWJM and pure Water Jet Machining (WJM) in terms of erosion mechanism involved in the material removal process. WJM is suitable for ductile metals which exhibits plastic deformation. On the other side, AWJM is suitable for hard materials that crack and fragment under impact causing brittle erosion. Erosion mechanism was focused by Ghazi Al-Marahleh, et al. with respect to impact angle and it was concluded that maximum erosion occurs at an impact angle of 90° for brittle materials while 20°-30° for ductile materials. AWJM is better than laser beam machining (LBM) which causes thermal damage and electro-discharge machining (EDM) which is limited to conductive materials. The Process was used by Weiyi Li et al 2016 for turning CFRP.

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III. MATERIAL DESCRIPTION

A. CFRP Composite MATERIAL: (Carbon and Coremat)

1) *Carbon:* Carbon is the 15th most abundant element available in the Earth's crust, and the fourth most abundant element in the universe by mass after hydrogen, helium, and oxygen. It is the second most available element in the human body by mass (about 18.5%) after oxygen. The atoms of carbon can bond together in different ways, resulting in various allotropes of carbon. The allotropes are graphite, diamond, and buckminsterfullerene. The physical properties of carbon differ widely with the allotropic form. For instance, graphite is opaque and black while diamond is highly transparent. Graphite is soft to form a streak on paper, while diamond is the hardest naturally occurring material known. Graphite may be a good electrical conductor while diamond features a low electrical conductivity. Under normal conditions, diamond, carbon nanotubes, and graphene have very best thermal conductivities of all known materials. All carbon allotropes act like as solids under normal conditions, with graphite being the most thermodynamically stable form at standard temperature and pressure. They are chemically resistant and it require high temperature to react with oxygen.
2) *Coremat:* Coremat may be a nonwoven, based on polyester fibres with a binder system that contains microspheres. It is used at thin core (bulker mat) or print blocker (liner) in fibre reinforced laminates, manufactured in Hand Lay-Up or Spray-Up processes. It should always be fully impregnated with resin. The microspheres in it prevent excessive resin up-take. The most important reasons for using Coremat are: Weight saving, Resin and glass saving, Stiffness increase, Fast thickness build-up. It has a core material is used in the center of a laminate. It can replace much heavier solid glass layers. Impregnated coremat features a density of 610 kg/m3 (38 lb/ft2), while Impregnated Chopped Strand Mat features a density of 1,500 kg/m3 (94 lb/ft3). This is a weight saving of 60%.

It saves resin and glass; it contains less resin than CSM: 1 mm (0.039 inch) of Coremat contains 0.6 kg/m2 (2.0 oz/ft2) while 1 mm (0.039 inch) of CSM contains 1 kg/m2 (3.31 oz/ft2).

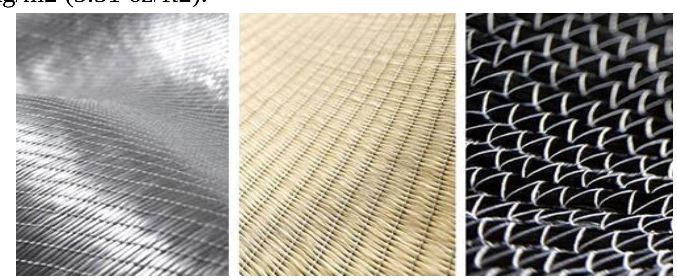

Fig 1: CFRP

IV. METHODOLOGY

A. Experimental Work and Procedures

A FLOW 3-axis CNC abrasive water jet machine (MACH1231b SERIES) is used, equipped with a JETPLEX pump capable of delivering pressure up to 55,000 psi (380 MPa). The machine has a cutting ability of 3 m x 2 m, and an accuracy of ±0.127 mm per 1 m at traverse speed up to 101 mm/min. Linear slots of 35 mm width were cut in CFRP laminate (parallel to fibres at 0º orientation) having 10.4 mm thickness. Abrasive water jet equipment and workpiece are shown in Figure.

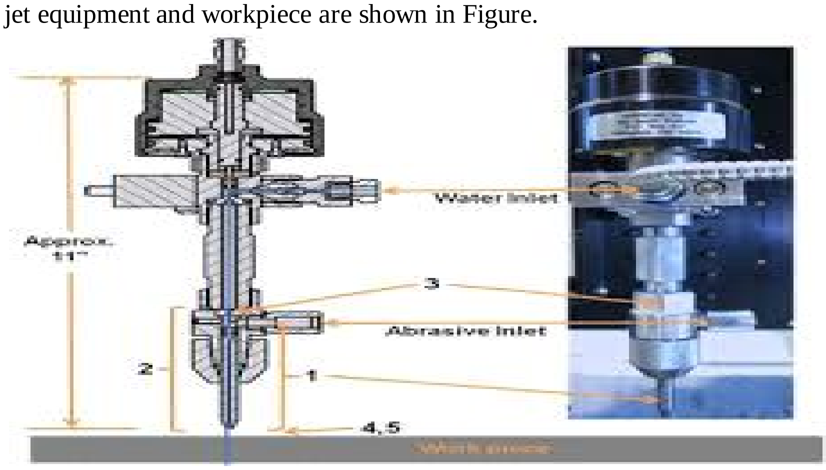

Fig 2: AWJM set up

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The material was autoclave cured aerospace grade CFRP composite consisting of epoxy resin and intermediate modulus T800 fibres laid up in two different lay-up configurations, Table 1. The work piece material had the specifications TORAY 3911/34%/UD268/T800SC-24K, which relates to resin type, resin content by weight (%), fibre areal weight (g/m2) and fibre type comprising 40 plies with 0.26 mm cured ply thickness and a total thickness of 10.4 mm.

Table 1: Lay-up configuration.

Lay-up 1	Lay-up 2
[45˚/0˚/135˚/90˚]5S	[45˚/0˚/135˚/135˚/135˚/90˚/45˚/45˚/ 45˚/0˚/135˚/135˚/90˚/45˚/45˚/0˚/135˚/135˚/90˚/45˚]2S

To study the performance of AWJM of different types CFRP plates an experimental design was devised. The process parameters and levels, in Table 2, were down-selected based on the literature review, as well as a set of pilot testing experiments. The main effects of the operating pressure (A), feed rate (B), standoff distance (C), and CFRP material type (D); as well as their interactions on the response parameters were obtained. Irregular shape and angular shaped abrasive mesh 80 was used for all tests. The abrasive was fed at a flow rate of 3 g/s, which was mixed with the water at the mixing chamber. The nozzle configuration consisted of a 0.30 mm orifice and a 1.02 mm diameter focusing tube. The tests were performed at an angle of 90º onto the surface of the CFRP plates.

$$Kerf\ taper = \frac{w_t - w_b}{2t}$$

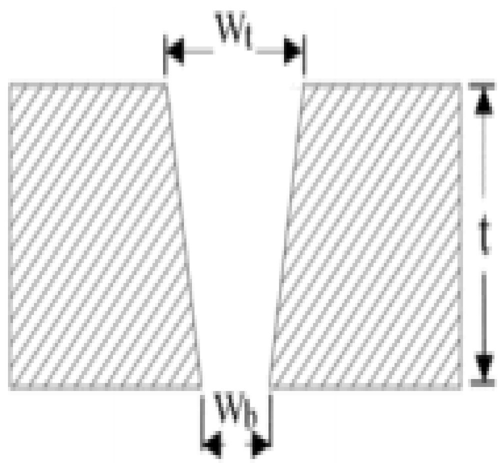

Fig 3: Kerf geometry schematic

$$Machinability\ Index\ (N_m) = \frac{v^{0.867}\ C\ Q\ t\ d_f^{\ 0.618}}{f_a\ p^{1.594}\ d_o^{\ 1.374}\ m_a^{\ 0.343}}$$

Where v is the feed rate in mm/min, C is constant (788), Q(1-5) is the cut quality factor determined on the bases the perpendicularity deviation u (equation 3), t is the cut thickness in mm, df is the focusing tube diameter (mm), fa abrasive factor (1 for garnet), p is the water pressure in MPa, do is the orifice diameter (mm), and ma is the abrasive mass flow rate in g/min.

Table 2: Process parameters and levels.

Symbol	Machine parameter	1	2
A	Operating pressure	100	350
B	Feed rate (mm/min)	50	150
C	Sandoff distance (mm)	2	4
D	CFRP Material type	Lay-up 1	Lay-up 2

V. CONCLUSION

A. *Kerf Width*

According to ANOVA, the standoff distance (C), feed rate B) and operating pressure (A) were significant at 0.001 with percentage contribution (PCR) of 60.44%, 20.04% and 16.35% respectively. Moreover, the interaction of (AC), (AD), and (ABC) were not significant. The main effects plot in Figure 3 shows that the top kerf width Wt increases with the standoff distance and water pressure while it decreases by increasing the feed rate. This agrees with findings in reference [24]. The top kerf width Wt was largely dependent on standoff distance as the jet tends to flare which makes the kerf width wider. The same trend was observed in the bottom width Wb but with slightly lower effect as shown in main effects plot of Figure 4**.**

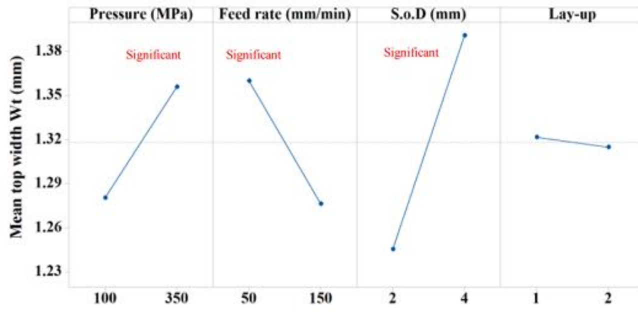

Fig 4: Main effects plot for top kerf width Wt.

The most significant factor affecting bottom width was pressure (significant at 0.001) with highest PCR of 64% followed by feed rate (7.21% PCR) and SoD (5.02%). In both cases, i.e. top and bottom, kerf width tends to decrease with higher feed rate due to shorter erosion time. The results showed a significant interaction between the operating pressure and the feed rate (AB). At high pressure (350 MPa) with the increase of feed rate decreases Wb, while it slightly increases at low pressure of (100 MPa). The lay-up exhibited has negligible effect on the width of cut. Despite the insignificance of lay-up as a factor, Lay-up 2 produced narrower cuts which reflects higher resistance to jet nd such lay-up demonstrated higher forces and temperatures during conventional slot milling operation when machined in same direction.

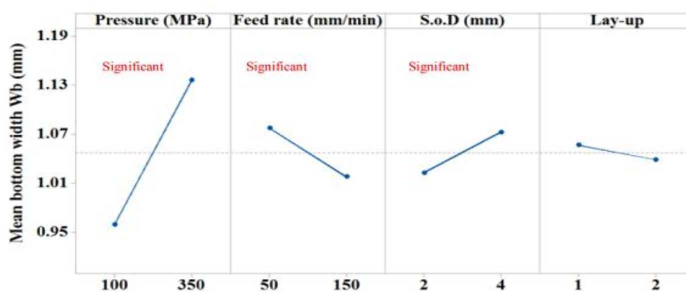

Fig 5: Main effect in bottom kerf Wb.

B. *Kerf Taper*

ANOVA results showed that the most significant factor affecting the kerf taper was the operating pressure (A) with 31% PCR followed by the standoff distance (C) with 27% and the interaction of the operating pressure and feed rate. Figure 5 shows the main effects of the kerf taper. Accordingly, use of high pressure and small standoff distance reduces significantly the kerf taper. The effect of using high feed rate on achieving small tapers is less significant, moreover the effect of using different CFRP material lay-up is negligible. Regarding the interaction AB, at low feed rate the effect of pressure was clear while at higher feed rate the effect of pressure diminishes.

C. *Machinability Index*

Main effects plot for calculated machinability index showed a similar trend to surface roughness Ra in terms of the response to pressure and feed rate, but on the other hand, negligible effect of S.o.D and Lay-up. The trend was suggesting low pressure and high feed rate for more accurate cuts which doesn't correspond to the experimental findings as discussed earlier which conclude a machinability index should be formulated for each composite material configuration.

D. Results

From the results of the AWJ-cutting of two types of CFRP lay-ups at different pressures, feed rate, &standoff distance, from that it can be concluded that:

1) The kerf width at the top and bottom of cut increases with pressure, standoff distance and decreases with feed rate. · For the smaller kerf taper it is recommended to use high pressure, small standoff distance and high feed rate.
2) The lay-up type of the material has no effect on the cut width and kerf taper.
3) For better surface quality, high operating pressure, low feed rate and small standoff distance are required.
4) Lay-up type 1 gives better surface quality than lay-up 2 CFRP material.
5) A machinability index should be formulated for CFRP.

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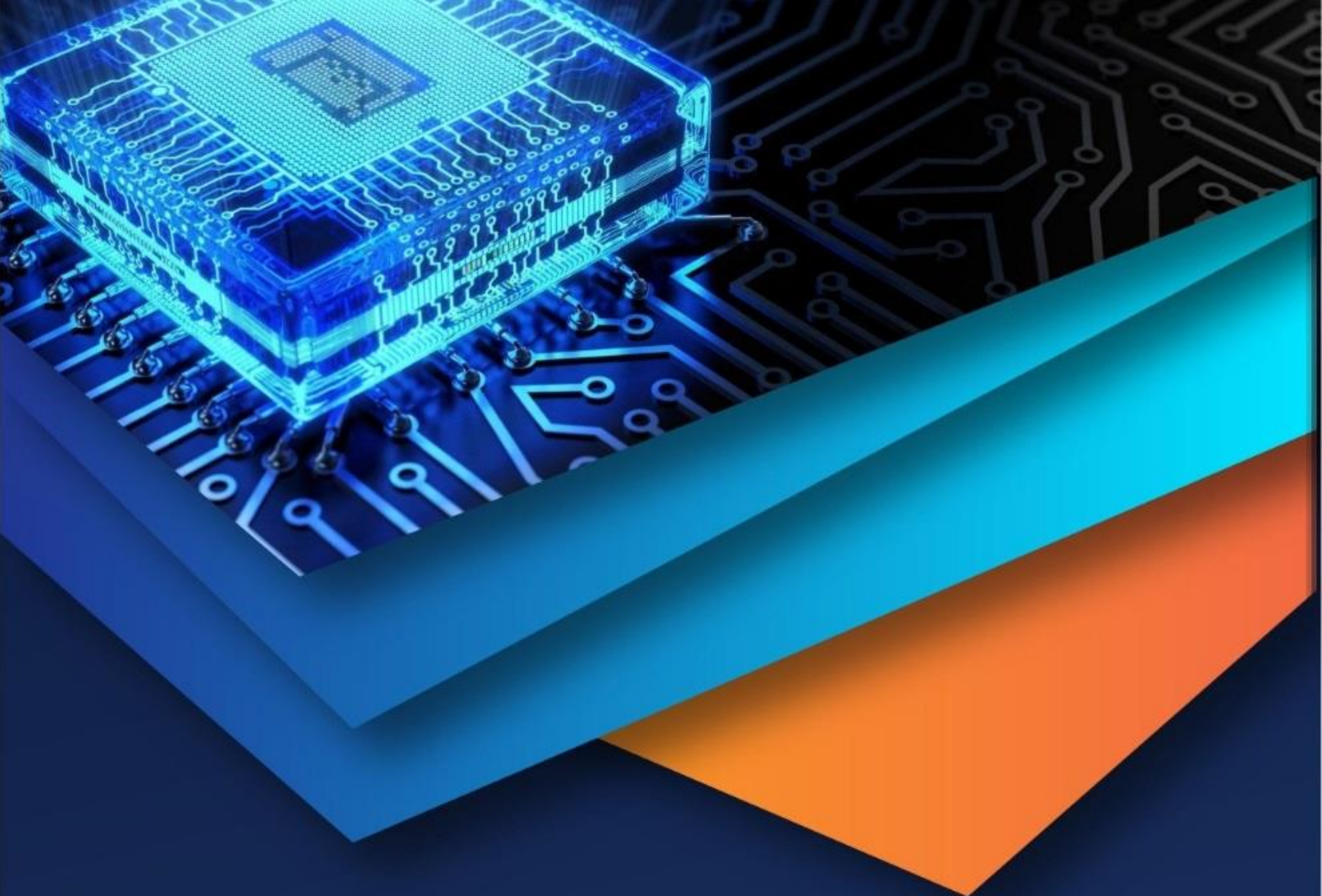

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