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Abrasive Water Jet Machining of Multidirectional CFRP Laminates

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Abstract

Abrasive water jet machining (AWJM) is widely used in aerospace, marine and automotive industries for trimming composites. However, AWJM demonstrates some challenges when cutting carbon fibre reinforced plastic (CFRP) composites materials such as cut accuracy and quality. More experimental work is needed to provide sufficient machinability databases for manufacturing engineers. This paper presents an experimental study and statistical analysis for cutting 2 lay-up configurations of multidirectional CFRP laminates. Different AWJM conditions including jet pressure, feed rate, and standoff distance are experimented using full factorial design of experiments. Machining process responses such as 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 presented.

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Keywords: CFRP; Composite; AWJ; Water jet; Cutting; Roughness, Machinability, Process Cost Model

1. 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 lead to delamination and fibre pull-out that reduce the fatigue strength and adversely influence the long term performance [1]. The abrasive nature of carbon fibres causes rapid tool wear which increases the cutting forces and heat generation, induces defects and deteriorates the surface integrity [2]. Depending on the cutting environment the, temperature can soar to exceed 300 °C which is higher than the glass transition temperature Tg [3]. There is a growing interest in non-conventional machining techniques in attempt to avoid the shortcomings associated with conventional machining. For instance, M. Saleem et al [4] and John Montesano et al [5] compared the fatigue strength of conventionally drilled holes in unidirectional CFRP as opposed to Abrasive Water Jet Machined (AWJM). The later exhibited 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 [6].

A fundamental difference 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 exhibiting plastic deformation. On the other hand, AWJM is suitable for hard materials that crack and fragment under impact causing brittle erosion. Erosion mechanism was in focus by Ghazi Al-Marahleh, et al [7] 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 advantageous over laser beam machining (LBM) which causes thermal damage [8] and electro-discharge machining (EDM) which is limited to conductive materials [9, 10]. The process was used by Weiyi Li et al 2016 [11] for turning CFRP.

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AWJM of composite materials was reviewed by a number of researchers and various experiments have been carried out to understand the effect of parameters on the process performance in different scenarios as, for example, in cutting unidirectional laminates [12], UD with a woven fabric CFRPs [13] and hybrid composites [14]. The material removal rate (MRR) is proportional to the power of the water jet and varies proportionally with the square of the diameter of the orifice. The machinability model of Zenge J et al [15] allowed the cutting traverse speed rate to be adjusted as a function of process parameters such as the required cut quality. The machinability index for GFRP and CFRP composite materials was determined experimentally by Alberdi, A et al [16]. Accordingly, a higher machinability index for GFRP and CFRP composites than metals was reported. Ultrasonic AWJM of ceramics was introduced by Tao Wang et al [17] with a model for the erosion depth and the material removal amount that were improved by vibration.

From surface roughness perspective, the effect of stand-off-distance (SoD) was controversial such that R. Selvam, et al. [14] and P. Unde et al [18] recommended higher SoD while lower SoD was suggested by and M. Voit [12] and Thirumalai [13]. Material configuration affected quality such that UD with fabric CFRP laminates exhibited lower surface roughness compared to full UD CFRP laminates. On the other hand, for better quality a higher pressure was said to be favorable by M. Voit [12] and S. Kumaran et al [13] which was contradicted by D. Parasad [18]. Higher feed rate was reported to cause rougher surface [18] while M. Voit [12] states the contrary. The controversy could possibly be due to different material configuration they tested, different nozzle configurations, abrasive quality, or high pressure systems.

Kerf width increased with operating pressure and SoD but it decreased at higher feed rates [19]. Kerf taper in AWJM determines the part accuracy and whether or not further machining, to have a square edge, is needed. In this regard, kerf width was found by D. Parasad to increase with fibre angle [18]. The use of high pressure resulted in smaller taper [18, 20]. Experimental investigation by Irina Wang MM et al [21] revealed that SoD was the dominating factor for minimization of the kerf ratio followed by traverse rate. Material configuration also has an effect such that AWJM was used by Alberdi A. et al [22] for drilling holes in CFRP/Ti6Al4V stacks. A positive taper angle was observed in Ti6Al4V while a negative angle was observed in CFRP leading to an X-type or barrel-type kerf profile depending on the stack configuration.

AWJM, if not optimized, may cause some defects such as delamination, fibre pullout, and particle embedment with potential defects from excessive heat. Delamination factor was reported to increase at large SoD and fibre orientation angle [18]. The delamination may occur at low abrasive mass flow rate and high feed rate; while fibre pull out at low jet pressure and high standoff distance [20]. Despite agreeing with the effect of flow rate and SoD, Ajit Dahanwadi et al. reported that delamination decreases with increase in jet pressure and feed rate. Abrasive flow rate was the predominant factor for delamination damage followed by traverse rate and jet pressure. Kamlesh Phapale et al [23] recommended the use of a backup plate during AWJ drilling in order to achieve lower delamination, hole size variation and surface roughness. Abrasive embedment occurred at high abrasive mass flow rate as well as small standoff distance [24].

Following all the controversial conclusions from literature there is a need to understand the effect of different parameters on the process. This paper presents experimental and statistical analysis of AWJM of multidirectional CFRP composites at different feed rate, nozzle distance and water jet pressure. Best AWJM conditions for two different lay-ups of CFRP that provide low kerf taper and low surface roughness were determined. The most significant parameters affecting the kerf width, kerf taper and surface quality were selected. A process cost model is also presented. The results and cost model can be useful for industrial end-users for developing machining knowledge for AWJM of composites.

2. Experimental work and procedures

A FLOW 3-axis CNC abrasive water jet machine (MACH 1231b SERIES) was used, equipped with a JETPLEX pump capable of delivering pressure up to 55,000 psi (380 MPa). The machine has a cutting envelope 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 0° orientation) having 10.4 mm thickness. Abrasive water jet equipment and workpiece are shown in Figure 1.

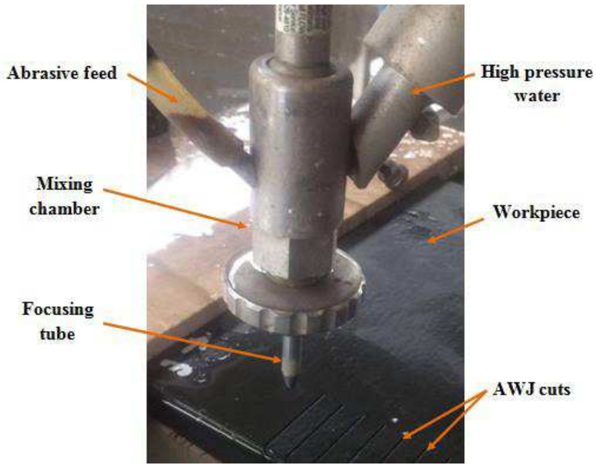

Figure 1: AWJ setup.

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 workpiece material had the specifications TORAY 3911/34%/UD268/T800SC-24K, which relates to resin type, resin content by weight (%), fibre areal weight (g/m^2) 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°]5$_S$	[45°/0°/135°/135°/135°/90°/45°/45°/ 45°/0°/135°/135°/90°/45°/45°/0°/135°/135°/90°/45°]2$_S$

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 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 90° onto the surface of the CFRP plates. Table 3 shows the test matrix comprising a full factorial design of experiments in which experiments were replicated twice. The output responses include kerf width (top and bottom), taper, and surface roughness. The top and bottom widths were measured using a Mahr MarVision MM320 optical microscope. On the other hand, the roughness was measured for a scanned area of 1.5 x 1 mm at 5.2 mm from the top surface of the cut using 3D and profile measurements KEYENCE VK-X100 laser scanning microscope in both longitudinal and transverse directions. Minitab 16 was used for statistical analysis of measured responses. The kerf taper ratio was calculated according to equation (1) where W_t is the top width of cut, W_b is the bottom width, and t is the cut thickness as shown in Figure 2. A machinability index (Nm) was calculated for all tests according to the empirical formula (2) found in reference [15]. The model provided AWJM database and was accepted by manufacturers. It was also used by other researchers in applications related to composite materials [16].

$$Kerf\ taper = \frac{W_t - W_b}{2t} \quad (1)$$

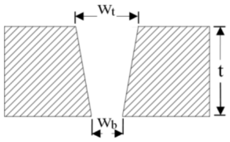

Figure 2: Kerf geometry schematic.

$$Machinability\ Index\ (N_m) = \frac{v^{0.867}\ C\ Q\ t\ d_f^{0.618}}{f_a\ p^{1.594}\ d_o^{1.374}\ m_a^{0.343}} \quad (2)$$

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, d_f is the focusing tube diameter (mm), f_a abrasive factor (1 for garnet), p is the water pressure in MPa, d_o is the orifice diameter (mm), and m_a is the abrasive mass flow rate in g/min.

$$Perpendicularity\ deviation\ (u) = \frac{W_t - W_b}{2} \quad (3)$$

Table 2: Process parameters and levels.

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

Table 3: Test matrix for a full factorial design of experiments 2^4.

Experiment number	Pressure (MPa)	Feed rate (mm/min)	S. o. D (mm)	CFRP Lay-up
1	100	50	2	1
2	100	50	2	2
3	100	50	4	1
4	100	50	4	2
5	100	150	2	1
6	100	150	2	2
7	100	150	4	1
8	100	150	4	2
9	350	50	2	1
10	350	50	2	2
11	350	50	4	1
12	350	50	4	2
13	350	150	2	1
14	350	150	2	2
15	350	150	4	1
16	350	150	4	2

3. Results and discussions

3.1 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. The lay-up type and error were negligible which means cutting 10 mm laminates of this material is not be affected by neither cutting directing nor the lay-up configuration. Moreover, the interaction (AC), (AD), and (ABC) were not significant. The main effects plot in Figure 3 shows that the top kerf width W_t 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 W_t was largely dependent on standoff distance as the jet tends to flare which makes the kerf width wider. The same trend was observed for the bottom width W_b but with slightly lower effect as shown in main effects plot of Figure 4.

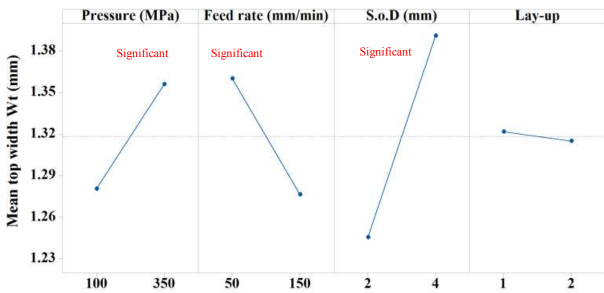

Figure 3: Main effects plot for top kerf width Wt.

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) the increase of feed rate decreases W_b, while it slightly increases at low pressure of (100 MPa). The lay-up exhibited negligible effect on width of cut. Despite the insignificance of lay-up as a factor, Lay-up 2 produced narrower cuts which reflects higher resistance to jet and such lay-up demonstrated higher forces and temperatures during conventional slot milling operation when machined in same direction [3].

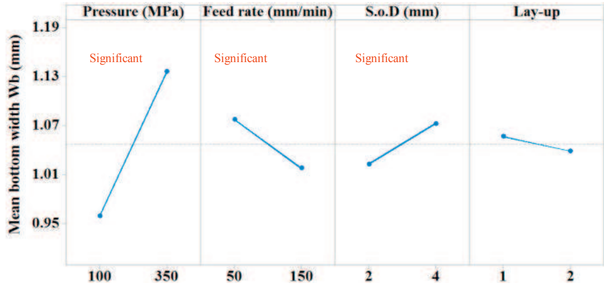

Figure 4: Main effect plot for bottom kerf W_b.

3.2 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% (both at 0.001) and the interaction of the operating pressure and feed rate (AB). Figure 5 shows the main effects plot for the kerf taper. Accordingly, the 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.

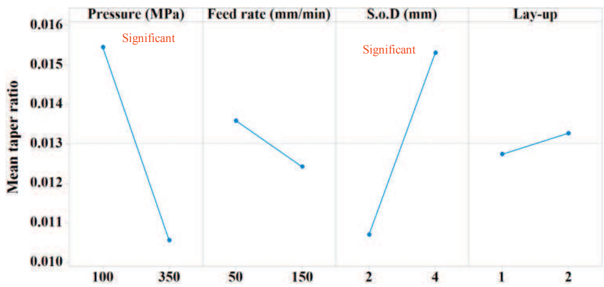

Figure 5: Main effects plot for kerf taper.

3.3 Cut quality and surface roughness

Low pressure together with high feed rate were not favorable for cutting thick laminates where the jet was unable to fully penetrate through the full thickness at the start of the cut, which meant that a “lead in” had to be added. The cut produced was not straight on the side of the jet exit (Test 5-8) as in Figure 6 a & b.

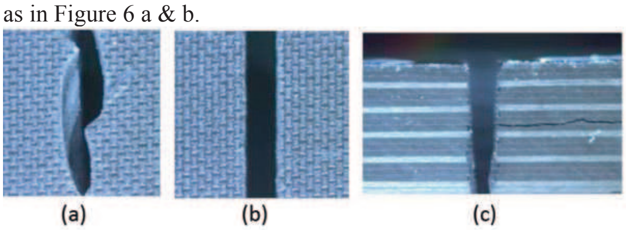

Figure 6: Bottom views of AWJ cuts of Lay-up 2 at 150 mm/min feed rate 4 mm standoff distance (a) 100 MPa Test-8 (b) 350 MPa Test-16 (c) delamination at 100 MPa 150 mm/min, 2 stand-off and Lay-up 1 (Test 5).

In such cases the jet may cause water wedging delamination (Figure 6-c) similar to that noted by [25] and also fibre pullout was observed. Striation lines from jet on surface were visible and their patterns (straight or curved due to jet lag) as well as pitches were affected by feed rate, being straighter and closely spaced at lower feed rate. Figure 7 shows the surface topography at different AWJM conditions with jet lag in case of high feed rate.

Although high pressure and low feed rate increase kerf width, the combination tend to produce straighter cuts and better surfaces of as low as 12 µm Ra in longitudinal. Ra roughness in transverse direction showed similar values. This suggests subsequent finishing operation to reduce roughness to 3.2 µm.

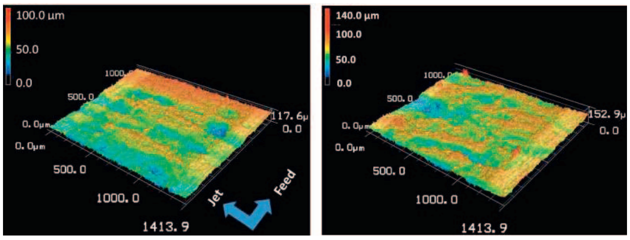

Figure 7: Surface topography at pressure of 350 and standoff of 2 mm cutting lay-up-1 at different feed rates (left) Test-9 at 50 mm/min (right) Test-13at 150 mm/min.

The peak to valley Rz in longitudinal (parallel to feed) roughness was higher than in transverse direction due to the first being determined by effect of feed rate and striation marks while in transverse direction the profile was affected by plies. Figure 8 shows the surface roughness main effects plot (in a direction parallel to feed). None of the factors showed any significance but pressure followed by Lay-up had the highest contributions respectively. Surface roughness Ra decreased at high pressure, low feed rate and smaller SoD possibly due to better jet profile nearer to nozzle. lay-up 1 exhibited better surface quality than lay-up 2 which was also evident in conventional milling of the same lay-ups in which 45° layers were responsible [3].

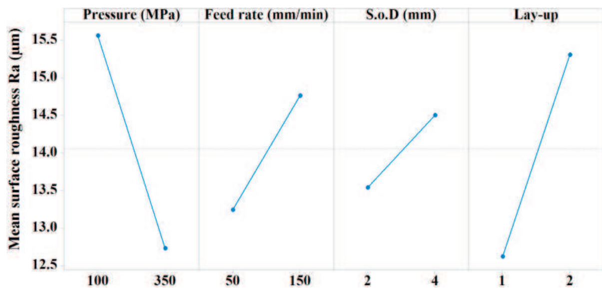

Figure 8: Main effects plot for longitudinal surface Ra at the middle.

From microscope scans, it was easier to identify individual layers on Lay-up 1 surface by the visible ply interface compared to Lay-up 2 as shown in Figure 9 which appears rougher and darker which reflects that Lay-up 2 being difficult to penetrate or possibly causing turbulent flow of jet. Less jet lag effect was noticed by increasing pressure at the same feed rate as in Figure 10 due to the higher kinetic energy of the jet at higher pressure which promotes erosion. Interactions AB, AC, BD and CD had significant effect on Ra. At high feed rate the effect of pressure becomes more evident that at low pressure. The effect of pressure is greater at small standoff distance. Material lay-up 1 shows significant change in Ra with respect to feed rate while lay-up 2 is more sensitive to Ra with standoff distance.

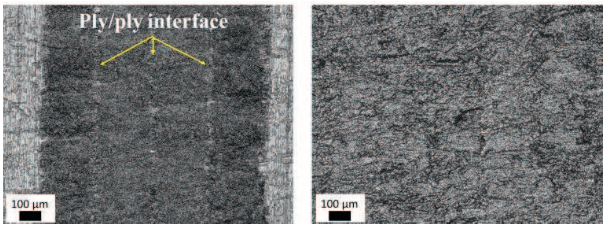

Figure 9: Surface images at 350 MPa, 50 mm/min feed rate and standoff of 2 mm cutting at different pressures (left) lay-up-1 Test-9/26 (right) Test-10/27.

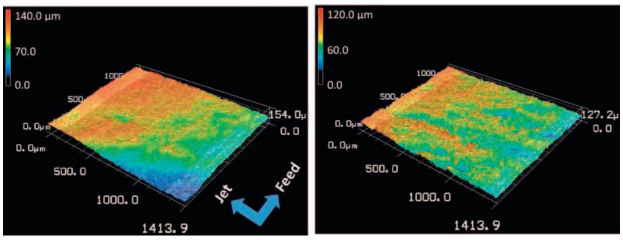

Figure 10: Surface topography at 150 mm/min feed rate and standoff of 4 mm cutting lay-up-1 at different pressures (left) Test-7 at 100 MPa (right) Test-15 at 350 mm/min.

3.4 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.

4. Process Cost

In AWJ the cutting tool is the water jet with abrasive particles. The most significant cost factor in running an AWJ system is the abrasive cost [26] as shown in the pie chart in Figure 11. While adding abrasives allows cutting virtually any material, abrasive consumption must be minimized for optimal economic performance [27]. Feeding abrasives in larger quantities may also be associated with clogging and process interruptions, which may result in additional cost increase. Moreover, the wear rate of the mixing tube may accelerate, which also adds to the cost of operation. Thus, reducing the abrasive consumption will generally enhance the economics, reliability and performance of the AWJ process. However, there are other costs such as power, pump and machine maintenance and general consumables that should be taken also into account for cost calculation. The process cost can be estimated based on the traverse rate used to trim a length of CFRP material and considering the cost for abrasive, water, consumables (i.e. intensifier pump and cutting head), power and maintenance of the machine. This estimation does not include labour cost and machine depreciation. The specific costs and equations used for the estimation of cost/m are stated in Table 4.

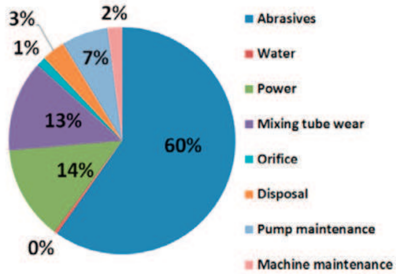

Figure 11: Cost breakdown for a 400 MPa AWJ.

Table 4: AWJ production costs.

Item	Abrasive Ca	Water Cw	Consum-ables Cr	Power Ce	Maintenance Cm
Specific cost	0.195 £/kg	0.0015 £/l	1.628 £/h	0.09 £/kWh	1,000 £/year 2000 h/year 5 £/h
Cost per unit length, Cl	Ca·ma/v	Cw·Vw/v	60Cr/v	60.Ce·Pe/v	60Cm/v

The total cost per meter can be found by the summation of the terms in Equation (4); where v is the traverse rate which varies with thickness. Added time should be considered for cornering and piercing.

$$\mathrm{Cl} = \frac{1}{v}[(\mathrm{Ca}\cdot\mathrm{ma}) + (\mathrm{Cw}\cdot\mathrm{Vw})] + \frac{60}{v}[\mathrm{Cr} + (\mathrm{Ce}\cdot\mathrm{Pe}) + \mathrm{Cm}] \quad (4)$$

Operating cost of AWJ machine is roughly £20/hr (machine manufacturer estimate). The cost per meter at a cutting speed of 150 mm/min would be ~£2/m. For slot milling, a 12 mm end mill will cost ~£60 (for an uncoated burr carbide) to ~ £300 (for a poly-crystalline diamond PCD) assuming a tool life criterion of 30 meters regardless of the tool condition, which is a common cut length target in aerospace industry, then the cost would be £2-£10/m. Milling produces high cutting forces and temperature induced damage [28] as well as of hazardous dust especially in dry environment which is favorable for hydrophilic composites and to prevent subsequent cleaning steps. Trimming same laminates using laser, they sustained severe thermal damage while using wire EDM was considerably slow and wire snapped.

5. Conclusions

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

- The kerf width at the top and bottom of cut increases with pressure, standoff distance and decreases with feed rate.
- For smaller kerf taper it is recommended to use high pressure, small standoff distance and high feed rate.
- The lay-up type of the material has no effect on the cut width and the kerf taper.
- For better surface quality, high operating pressure, low feed rate and small standoff distance are recommended
- Lay-up type 1 gives better surface quality than lay-up 2 CFRP material.
- A machinability index should be formulated for CFRP.
- A process cost model that incudes costs of abrasive, power consumption, consumables, water and maintenance was presented. The model allows for estimating the meter of material trimmed. It was concluded that AWJM of CFRP may be a cheaper option than milling.

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