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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.

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.

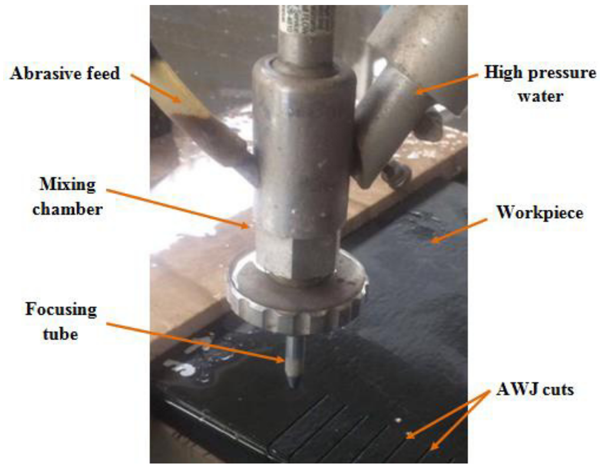

Figure 1: AWJ setup.

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
$[45°/0°/135°/90°]5_S$	$[45°/0°/135°/135°/135°/90°/45°/45°/45°/0°/135°/135°/90°/45°/45°/0°/135°/135°/90°/45°]2_S$