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Surface and machining induced damage characterization of abrasive water jet milled carbon/epoxy composite specimens and their impact on tensile behavior

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ABSTRACT

Controlled depth milling of composites structures by abrasive water jet (AWJ) is a new area of machining being explored and knowledge on this is bare minimum. Hence it is essential to investigate surface quality and damage induced to ascertain their mechanical reliability. Here, the mechanism of material removal is manifested by erosive wear. In this study, carbon fiber reinforced plastic (CFRP) laminates are milled using AWJ process and surfaces generated by varying process parameters are characterized using roughness systems, X-ray tomography and scanning electron microscopy (SEM). SEM images reveal presence of damages in form of craters, ridges, broken fibers and embedded abrasive particles. Crater formation due to erosion phenomenon is affected by jet pressure. It is seen that the crater volume increases by around 500% when pressure varies from 80 MPa to 140 MPa. In the literature reviewed correlation between roughness of the machined surface and the mechanical behavior is ambiguous and remains an open problem. Hence, novel attempt has been made to analyze the influence of damage (crater volume) on tensile strength. Mechanical tests on specimens with varying surface texture and crater sizes reveals that tensile strength of machined specimens is more influenced by crater volume rather than surface roughness.

1. Introduction

Fiber Reinforced Plastics (FRPs) are a class of composite materials offering several advantages such as: a very high strength-to-weight ratio/high modulus-to-weight ratio and corrosion resistance. These advantages make them a widely used material in aerospace, marine, robotics, construction, transportation, sporting goods, and defense applications. Usage of composites in any of these fields needs a specific shape, size, load bearing capacity, geometrical and damage tolerance. Hence, to obtain these attributes they undergo series of processing operations starting from mold curing to machining phase. Though they are manufactured to near net shape; secondary machining operations like trimming, milling, grinding and hole making may always be required to produce the final functional component [1–3]. In addition, machining is also employed for repairing damaged sections of composite structures in service which is usually done by milling out the damaged section and patching it with new material [4,5].

Milling of FRPs especially by conventional methods is practically difficult owing to their highly heterogeneous nature due to the presence of distinctive phases of fiber reinforcements and plastic matrix which have a huge variation in their mechanical, thermal and physical properties. This makes machining of composites a complex problem because the mechanisms of material removal are strongly derived by relative angle between the direction of the cutting speed and the fibers direction [1,3]. Research conducted on conventional milling of FRPs shows many kinds of damages like delamination, fiber pull-outs, matrix recession, interlaminar cracks and thermal degradation whose nature, size and position chiefly depend on machining parameters and fiber orientation with respect to cutting direction [1–3,6–9]. Also conventional milling leads excessive and premature tool wear because of abrasive nature of the carbon fibers and also dangerous levels of dust is generated which affects the environment and is also harmful to the operator [6]. All these limitations led to rapid advancement of machining FRPs by non- conventional techniques like abrasive water jet, laser, and electrical discharge machining.

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However, several studies report numerous defects delamination, matrix cracking, matrix degradation and burnout matrix recession, thermal damage in laser machining [7]. Also, other damages like high thermal degradation, recast layer and delamination along the spark channel can be observed in electrical discharge machining and defects like delamination, grit embedment and striations in AWJ machining [1,10,11].

The AWJ machining process is a well-established non-conventional machining process and is proved to be effective for trimming a wide range of materials including composites [10–12]. Many studies have demonstrated effective approaches for trimming FRPs by AWJ with respect of the material integrity when the machining is conducted with optimal machining parameters [8,10,13]. In comparison with conventional machining, AWJ machining imposes minimal forces on the workpiece, does not require any specific tooling, does not produce any heat affected zones and in terms of impact on environment, abrasive water jet process is considered to be least harmful. These advantages encourage exploring more possibilities of using AWJ machining for composite materials. Recently, Haddad et al. [8] have shown that, the compressive failure stress of specimens trimmed by AWJ process is 15% superior to those trimmed by conventional process (burr tool). Owing to these advantages, during the last decade, AWJ machining process has been used for turning and milling (with controlled depth of cut) of metals [1,14–17,31] and some studies have demonstrated the feasibility of this process for composites too [18,19]. Studies on milling Titanium alloy by Shipway et al. [31] prove that AWJ can produce industrially acceptable components with careful optimization of process parameters to reduce surface waviness and damage. Eventually, AWJ milling can be considered as an alternative solution to overcome the conventional milling of composite materials, and especially for repairing applications by patching techniques. It is important to mention that in the literature, when milling of composites by AWJ process the machining quality obtained and its impact on mechanical behavior of composites structures has not yet investigated.

It is known fact that, every machining technique has its own physics of chip formation and the mechanism of material removal will impact the surface properties of the generated surface. In AWJ machining the material removal is due to phenomenon of erosion by solid particle impact. Sheldon et al. [20] propose that, during trimming, the material removal occurs by erosion phenomenon where propagation and chipping due to the high contact stresses arising during impact. The solid particle impact causes stresses which in turn causes cracks in the material surface however in addition to this lateral crack formation also takes place after repeated impact by abrasive particles which is the main cause of material removal [20]. Arola et al. [21,22] and Ramulu et al. [10,23] focused on trimming of graphite-fiber reinforced epoxy by an abrasive water jet and explain that the mechanism of material removal is mainly by micro-mechanism of cutting which is evident by presence of broken fibers or fiber pullout over the entire cutting front. In this case, authors explain that, the material response is determined by the brittle properties of the fibers. Thereby, a combination of micro-machining and the brittle fracture of the fibers are observed when the jet stream is impinging on the composite workpiece. Also, variations in flow patterns due to machine constrains will also change the erosion conditions and resulting surface properties wholly depend on the milling parameters, for example, Studies on milling Titanium alloy by Shipway et al. [31] show that increasing jet traverse speed will increase surface roughness but decrease surface waviness. It is clear that due to the material removal mechanism there is degradation of the workpiece surface. Previously several researchers have tried to link machining quality with mechanical behavior. Industrially, arithmetic average surface roughness (Ra) is one of the important parameter used to quantify and qualify the machined surface [8,13,24–30]. However, when this parameter (Ra) is considered for composite materials, contradictory results have been seen. Ideally good machining quality is quantified by low value of Ra which should lead to better mechanical performance. For example, the results from mechanical tensile tests out on unidirectional glass fibers/epoxy resin samples oriented at $+45°$ relative to the axis of loading have shown that the tensile strength increases with the increase of the average roughness (Ra) [29]. On the contrary, the results of compressive mechanical tests conducted on UD specimens oriented at 0° [30] have shown that the failure stress decreases with the increase of the surface roughness. Similarly, in work of Haddad et al. [8] when trimming of multidirectional carbon/epoxy specimens by AWJ and subjected to compressive loading, it was observed a reduction in the compressive strength with the diminution of the Ra. However, when trimming is conducted by conventional machining process the evolution of the compressive strength in function of the roughness Ra is random, i.e.; specimen with higher Ra value exhibited increased compressive strength. Also, investigations on compressive strength of FRPs conducted by Ramulu et al. [13] show that the surface roughness of the machined surface (trimming) does not have a clear impact on the compressive strength. However, the major factor for the compressive strength reduction is the extent of delamination caused by machining [13]. It is clear that, average surface roughness, Ra developed initially for machining metallic materials cannot be used with all the confidence for the characterization of the machined surface of composite materials.

The scope of present work focuses on the influence of AWJ milling parameters (viz. jet traverse speed, jet pressure, scan step and stand-off distance) on surface characteristics and also the extent of damage induced during material removal by milling for unidirectional carbon/epoxy laminates (UD-CFRP). In order to understand the influence of different machining parameters on milled depth, material removal rate (MRR), surface texturing (broken fibers, matrix degradation, crater volume, etc.) a full experimental design is employed. In addition, the machining damage is quantified by analyzing surface topology and calculating the crater volume, thanks to the 3D contour processing. Lastly, the impact of machining damage on the tensile behavior of the composite specimens is studied and correlated with crater volume (extent of damage). For this purpose quasi-static tensile tests have been conducted on different composite specimens which are characterized with different level of quality and damage.

2. Materials and methods

2.1. Composite material

Carbon fibers reinforced plastic (CFRP) laminates were made using unidirectional prepregs supplied by Hexcel Composite Company, referenced under HexplyT700-M21.A unidirectional (UD) laminate with 12 plies and dimension of 300 × 300 mm was used for the tests. The laminate was prepared in a controlled atmosphere (white room) and compaction was carried out using a vacuum pump. A mold for the laminate was prepared and placed in a vacuum bag and evacuated to 0.7 bars. Curing was then conducted at 180 °C for 120 min during which the pressure was maintained at 7 bars in an autoclave (as recommended by Hexcel Composite Company). With this process of manufacturing, the nominal fiber volume fraction is around 59% and the theoretical thickness of plate is around 3.12 mm. From the laminate, 12 coupons of size 280 mm × 20 mm were cut using AWJ and each coupon was used for 9 tests with different matching parameters