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Open hole fatigue testing of laser machined MD-CFRPs

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ABSTRACT

The effect of fiber laser machining (FLM) on multi-directional carbon fiber reinforced plastics (MD-CFRP) with [0/90/45/−45]s lay-up was studied under tension-tension fatigue with stress ratio $R = 0.1$ for an open hole fatigue (OHF) test configuration. The FLM parameters were chosen to yield a heat affected zone (HAZ) corresponding to a damage factor of approximately 1.4. The growth of this initial damage under tension-tension fatigue was investigated using digital image correlation (DIC), and damage growth characterization was carried out using scanning acoustic microscopy (SAM) and micro computed tomography (micro-CT). The endurance limit of the MD-CFRPs was evaluated by examining the fatigue life at 70, 50 and 30% of its ultimate tensile strength. Results show a strong correlation of damage mode on the applied load levels like conventionally machined samples.

1. Introduction

Fiber reinforced plastics (FRPs) find wide variety of applications in aerospace and automotive industries owing to their high specific strength and stiffness, durability and tailorability among other advantages [1]. FRPs being difficult to machine, one of the main challenges with widespread usage of FRPs is to determine the minimally damaging machining process to ensure better structural integrity of the component. Due to the inherent heterogeneity and anisotropy, conventional machining damage in FRPs are several, such as matrix cracking, fiber pull-outs, fuzzing, spalling, delamination, tool wear, thermal degradation, and excessive dust generation [2–5]. Unconventional machining such as laser processes [6–8], abrasive water-jet [9], and ultrasonic machining [10], have been studied by various research groups.

Laser machining has received considerable attention due to non-contact, rapid and environment friendly mode of cutting [11] and is especially advantageous in machining of hard-to-cut materials [12]. However, heat affected zone (HAZ) is a major disadvantage of laser machining [13]. Due to the inhomogeneous properties exhibited by the composite constituents, the extent of HAZ tends to be higher along the fiber direction in laminated FRPs [13]. HAZ occurs due to localized laser heating, creating thermal gradients and related stresses. During laser machining of composites, the matrix phase of the FRPs recedes creating a region with highly localized matrix recession and fiber-matrix debonding [13]. In order for laser machining to be used as a secondary processing technique, it becomes important to understand the effect of laser machined damage on the structural integrity of the component.

Determination of useful life of any component in terms of loading cycles is a critical part of design. Open hole fatigue (OHF) testing of FRPs offer an apt configuration to study the effect of machining damage on structural integrity [14]. OHF testing procedure is well documented and routinely performed on composite components during the design phase [15,16]. Traditionally, the effect of machining damage on structural integrity has been incorporated by modifying the stress concentration factor due to machining damage [17,18]. However, the correlation between structural integrity and propagation of inherent machining damage mechanisms during OHF testing has not been reported extensively. This is particularly true for laser machining.

Nixon-Pearson et al. [19] experimented on 2.5 mm thick carbon fiber epoxy laminates at a maximum load of 60% of tensile ultimate strength (σ_{UTS}), cycle frequency of 5 Hz and stress ratio R of 0.1. Holes of diameter 3.1 mm were pre-drilled using tungsten carbide drill bits. At 60% σ_{UTS}, the laminates successfully surpassed 10^6 cycles without any failure. Analysis of the laminates by X-ray computed tomography (CT) images, shows that the initial damage starts to propagate out of the hole edge via delamination and matrix cracking. Montesano et al. [14] compared both the static and fatigue performance of conventional drilled (CD) and abrasive water jet machined holes of satin-woven carbon fiber/epoxy plates using OHF tests. While static properties did not exhibit a correlation to machining damage, long term cyclic tests revealed that the plates with CD holes exhibited higher stiffness degradation as compared to abrasive water jet machined holes.

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Essentially, Montesano et al. [14] demonstrated that the type of machining process also plays a significant role in ascertaining the structural integrity of a composite component, and not just the extent of machining damage.

In an earlier work by the authors [12,13], a detailed investigation of machining damage mechanisms for fiber laser machining (FLM) were reported. Both glass and carbon FRPs were investigated with unidirectional (UD) and multi-directional (MD) configuration to quantify the effects of anisotropy. Effect of cutting parameters on machining damage were also characterized in terms of damage factor (F_d) for both machining processes based on images acquired through scanning acoustic microscopy (SAM). F_d signifies delamination in the case of conventional drilling while it signifies HAZ in the case of FLM. It was concluded that, although the time for laser setup and machining is significantly lower for FLM, machining damage in FLM is higher than corresponding CD obtained from polycrystalline diamond tools. However, correlating machining damage to load-carrying capability during both static and cycling loading of the composite structure needs to be studied systematically prior to confirming the better machining process.

In the current work, the effect of fatigue loading on open hole MD-CFRP laminates is studied. The open holes were machined with FLM at 400 W and 500 mm/min velocity. Prior to fatigue loading, SAM was used to evaluate the F_d due to heat affected zone. Open hole tensile tests yielded the average static tensile strength σ_{UTS}. Tensile-tensile OHF experiments were conducted at maximum load of 70, 50, and 30% of σ_{UTS} with a stress ratio R of 0.1 until either of the following conditions were satisfied: degradation of stiffness by 15% or 10^6 cycles or catastrophic failure, whichever was earlier. *In-situ* full field displacement measurements made with digital image correlation (DIC) conducted during the entirety of the fatigue testing was used to analyse the deformation patterns and correlate to the failure mechanism initiation, growth and final fracture as observed. Endurance limit for FLM machined OHF samples have been identified for the chosen F_d. In brief, a systematic correlation of the machining damage to load-carrying capability under static and fatigue loading was exercised to effectively evaluate the laser machining process. The damage mechanisms in composites are a function of applied load and hence fatigue failure mechanisms needs to be understood in detail.

2. Materials and methods

2.1. Sample preparation

Quasi-isotropic MD-CFRP laminates with [0°/90°/45°/−45°]s stacking sequence were manufactured by vacuum assisted resin transfer molding (VARTM) process as described in detail elsewhere [20]. All the laminates were approximately 2.7 ± 0.3 mm in thickness. Volume fraction tests were carried out using acid digestion for CFRPs and was found to be approximately 55–60% fiber and less than 2% porosity. A hole diameter of 6 mm was laser machined on the samples (see Figs. 1a–1c) at 400 W and 500 mm/min. In compliance with the ASTM D5677/D7615, the ratio of hole diameter to thickness was maintained at approximately 2. The ratio of sample width to hole diameter ratio (w/D) of 6 was chosen. Hence, samples of 36 mm width were cut for static and fatigue tests. The samples were cut from the laminates using a slow-speed diamond wheel cutting machine. The length of the samples were limited to 217 mm. End tabs of 45 mm length were cut out from the same MD-CFRP laminate and glued to either ends of the sample of equal thickness on both sides using Araldite®. OHT and OHF tests were conducted on samples with laser machined holes as per the procedure outlined in ASTM standard D5677/D7615. In the case of OHF tests, the frequency of loading was 5 Hz.

2.2. Fiber laser machining

Holes of 6 mm diameter were machined using fiber laser system that uses a 10.70 μm wavelength laser (SPI lasers, UK) operating at a maximum of 400 W in continuous mode. The focused spot size of the laser beam is 150 μm. Nitrogen gas at 10 bar pressure was used coaxially to the laser beam both for protection of the laser optics as well as to assist the machining process. About 1.5 mm standoff distance between nozzle and workpiece was maintained. The schematic of the setup is shown in Fig. 1a. Machining with laser causes thermal damages termed as heat affected zone (HAZ). In an earlier study conducted by the authors, it is reported that laser machining demonstrates 'thresholding' behaviour wherein machining (or material separation) does not occur at laser powers less than 400 W [13]. Additionally, altering the laser cutting speed for a fixed laser power of 400 W did not exhibit considerable variation in the experimentally determined damage factor, F_d. F_d is defined as the ratio of maximum damaged diameter (D_{max}) to the intended diameter (D_o) for both top (laser entry side) and bottom (laser exit side) surfaces [21,22]. Thus, in the current study, a laser power of 400 W and a cutting speed of 500 mm/min was used to drill all the holes in the MD-CFRP laminate. Detailed laser machined damage analysis has been reported elsewhere in [13].

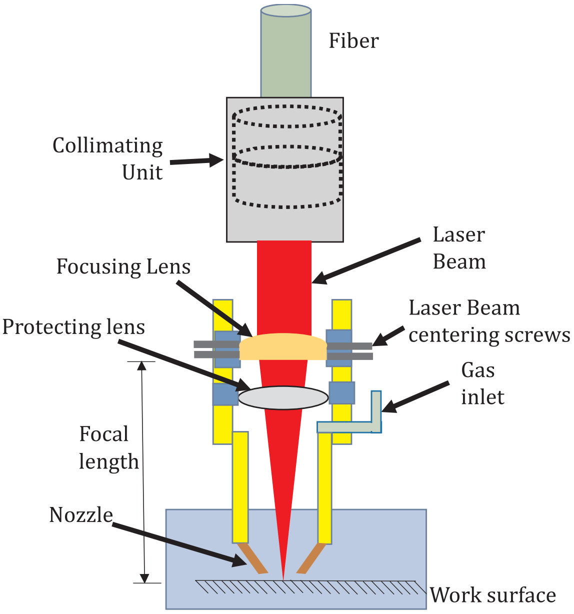

Fig. 1a. Laser machining setup. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Open-hole tensile and open-hole fatigue testing (OHT and OHF)

Prior to fatigue testing, OHT static tests were performed in accordance with ASTM standard D5677 [15]. An Instron 1341 servo hydraulic test machine was used for all the experiments. The samples with pre-glued end tabs were held via hydraulic grips (see Figs. 1b and 1c). All tests were conducted at a constant displacement rate of 0.5 mm/min. The tests were carried out until either a significant decrease in load or sample separation occurred. For OHT, strain measurements were carried out using a 25 mm gage length extensometer by placing the extensometer probes along the sample edges symmetrically across the hole centre.

Tension-tension OHF tests were carried out in accordance with ASTM D7615 at an R ratio (i.e., P_{max}/P_{min}) of 0.1. The average of the maximum strength obtained from OHT tests was designated as σ_{UTS}. Cyclic sine wave loading at a frequency of 5 Hz with maximum amplitude (P_{max}) equal to 70, 50 or 30% of σ_{UTS} was applied to the samples. Each test was executed for a million (10^6) load cycles unless failure, defined as 15% degradation in stiffness or separation of the sample [23,24], occurred first. The stiffness of the OHF specimen at