AN INVESTIGATION OF THE EFFECT OF THE MACHINING PROCESSES OF CIRCULAR HOLES ON THE MECHANICAL BEHAVIOUR OF FLAX FIBER REINFORCED POLYMER

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Abstract

In this work we investigated the influence of the machining quality on the mechanical behavior of natural fiber reinforced composite material selected for manufacturing bone fracture plates. The material used in this study is a Flax Fiber Reinforced Polymer (FFRP). Two types of composite lay-up were used to conduct this study: $[0]_{16}$ and $[\pm 45]_{16}$ laminates. The experimental study was carried out on several composite plates drilled with a Conventional Machining (CM) process using a cutting tool and an abrasive water jet machining (AWJM) process. In order to study the impact of the process of machining on the mechanical behavior of the composites, infrared thermography coupled with fatigue cyclic tests were performed to assess the temperature and the damage evolution in these FFRP plates.

1. Introduction

Polymer materials reinforced with plant based fibers such as flax, hemp, jute and sisal have been considered by numerous studies as potential alternative materials to glass-fiber reinforced plastics (GFRP) [1,2,3]. Like GFRP, natural fiber based composites are inherently more susceptible to variations in manufacturing processes. Besides, in structural applications, such materials are often subjected to cyclic loads which cause progressive damage and may lead to long term failure of the structure.

The origin of the present work lies within the framework of an ongoing research program on the development of bio-based materials for use in orthopedic long bone fracture plates. The bone fracture plates are structures that contain machined holes that allow their fixation on the fractured bone. These holes induce a discontinuity and strength reduction in the composite structure, which happens due to the development of stress concentrations around the notched area. It is important to understand the sensitivity of composite laminates to the machined edges and notches. Machined edges sensitivity has been influenced by many factors such as laminate (thickness, ply number, and lay-up), notch (dimension/diameter and shape), and material's properties [4, 5, 6].

The aim of this work is therefore, to investigate the influence of the machining process on the fatigue behavior of the natural composite materials selected for manufacturing the bone fracture plates. The material used in this study is a Flax Fiber Reinforced Polymer (FFRP). Two types of composite lay-up were used to conduct this study: $[0]_{16}$ and $[\pm 45]_{16}$ laminates.

The experimental study was carried out on several composite plates drilled with with a Conventional Machining (CM) process using a cutting tool and an abrasive water jet machining (AWJM) process. In order to study the impact of the process of machining on the mechanical behavior of the composites infrared thermographic tests coupled with fatigue cyclic tests were performed to assess the temperature and the damage evolution in the composite plates as demonstrated on prior works [7].

2. Materials and Methods

2.1. Composite Specimens Preparation

Flax/epoxy prepregs were purchased from LINEO, Belgium. The product type is a unidirectional (UD) flax fiber treated by a patented sizing and drying process (US Patent No. 8080288) and impregnated with partially cured epoxy resin system (Huntsman LY5150). The flax/epoxy prepreg has an areal density of 180 g/m^2 with an epoxy content of 50 % per weight. Flax/epoxy plates were manufactured using 16 layers of 300 mm X 300 mm sheets with a $[0]_{16}$ unidirectional ply orientation and $[\pm 45]_{16}$. The flax material was placed on a plate in a sealed vacuum bagging set-up and cured in an autoclave at 150°C for 2h under 4 bar pressure while a 0.7 bar vacuum was maintained during the entire cure cycle.

Specimens were individually cut from the laminate plates in rectangular beams using a diamond wheel. All specimens were 36 mm (width), 250 mm (length) and 3 mm (thickness) (**Figure 1**). Circular hole of 6 mm diameter was machined at the center of each composite specimen with computer numerical control (CNC) machine using carbide drill bit for conventional machining technique (CM), while water-jet machining technique with the addition of abrasive particles was considered for non-conventional machining technique. For CM, spindle speed of 1050 rev/min and feed rate of 0.13 mm/rev were used for drilling holes, while water-jet pressure of 170 MPa, particle size of 180 microns and a standoff distance of 4 mm was kept constant during the machining of the holes with abrasive water-jet machining (AWJM) technique.

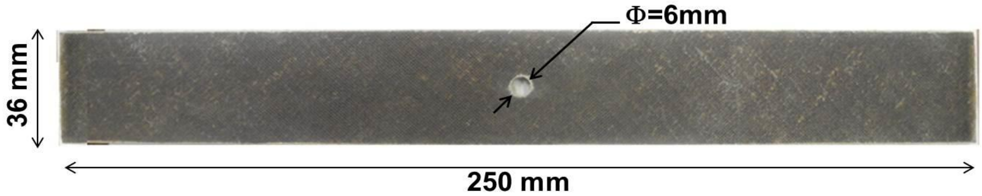


Figure 1. Flax/Epoxy specimen with geometrical specifications

2.2. Testing Procedures

Static tensile tests and tension-tension and fatigue tests were conducted on a servo-hydraulic MTS test machine equipped with a 100 kN load-cell capacity. Strain measurements were obtained using an extensometer with a 25 mm gage length, placed at the center of all specimens. The static tests were performed in accordance with ASTM standard D3039, at a displacement rate of 2 mm/min. The ultimate tensile strength (UTS), ultimate strain, and modulus of the composite were accordingly determined. Fatigue experiments were conducted in accordance with the ASTM standard D3479 at room temperature and under load control with a minimum to maximum stress ratio of 0.1 and a cyclic frequency of 5Hz. The samples were mounted in the grips using a 40 lb.in torque. The temperature rise versus applied cyclic load curves were obtained from stepwise cyclic load increment tests whereby the cyclic load was kept constant for a specific number of cycles, namely 7000 cycles, in order to reach the steady temperature. Starting from the lowest cyclic load levels, loading was incremented stepwise, 7000 cycles at each step, and so forth until failure of the sample has occurred. The overall rise in specimen's temperature was recorded for each cyclic load level at the end of each 7000 cycles run. Those tests were followed by conventional fatigue tests in order to determine the composite's S-N curve.

The IR camera (model FLIR Silver 420) was also employed during fatigue tests. The camera was fixed on a tripod and placed at a distance of 100 cm from the specimens gripped in MTS testing machine to capture stable images without any vibration. The IR camera was equipped with an integrated motorized lens and could be easily focused using the software. The camera's resolution is 320 X 240 pixels with a temperature sensitivity of 20 mK for accurately monitoring the temperature variation. All tests were performed in laboratory ambient temperature (24°C).

The inspection of machined surface was carried out using a scanning electron microscope SEM (JEOL JSM-6380, Tokyo, Japan). Microscopic observations were conducted after the sectioning of a number samples, before the fatigue tests in order to examine the quality of the machined surfaces, and of post-fatigue tested specimens.

3. Damage Assessment and Determination of the HCFS using IR Thermography

Using the abovementioned IR camera we recorded the temperature increase of the flax/epoxy composite laminates during stepwise loading fatigue tests. The thermograms presented in Error! Reference source not found.**2 (a, b) and (c, d)** present the temperature increase as a function of the number of cycles for different loading levels for the $[0]_{16}$ and $[\pm45]_{16}$ laminates, respectively. It is clear from the plots that after 4000 cycles the temperature rise levels off and reaches a constant temperature. During all the tests a temperature gradient appears on the surface of the sample with the hottest zone in the vicinity of the hole where the failure happened later because of the stress concentration.

The increase in temperature during the cyclic loading is directly proportional to the damage in the tested specimens. Generally, the increase in temperature is related to matrix degradation, fiber pull-out/breakage and delamination during fatigue cyclic loading [7,8], The elevation of temperature during the cyclic tests in **Figure 2 (a)** and **Figure 2 (b)** are similar for the $[0]_{16}$ laminates machined with both machining techniques, hence no significant difference in the damage evolution in the laminates. However, a noticeable difference between specimens machined with CM and AWJM can be observed on profile of the temperature elevation of $[\pm45]_{16}$ laminates **Figure 2 (a)** and **Figure 2 (b).** The higher temperature elevation in the specimens machined with CM technique is due to the fiber/matrix delamination and debonding which resulted in further increase of temperature as the number of loading increases.

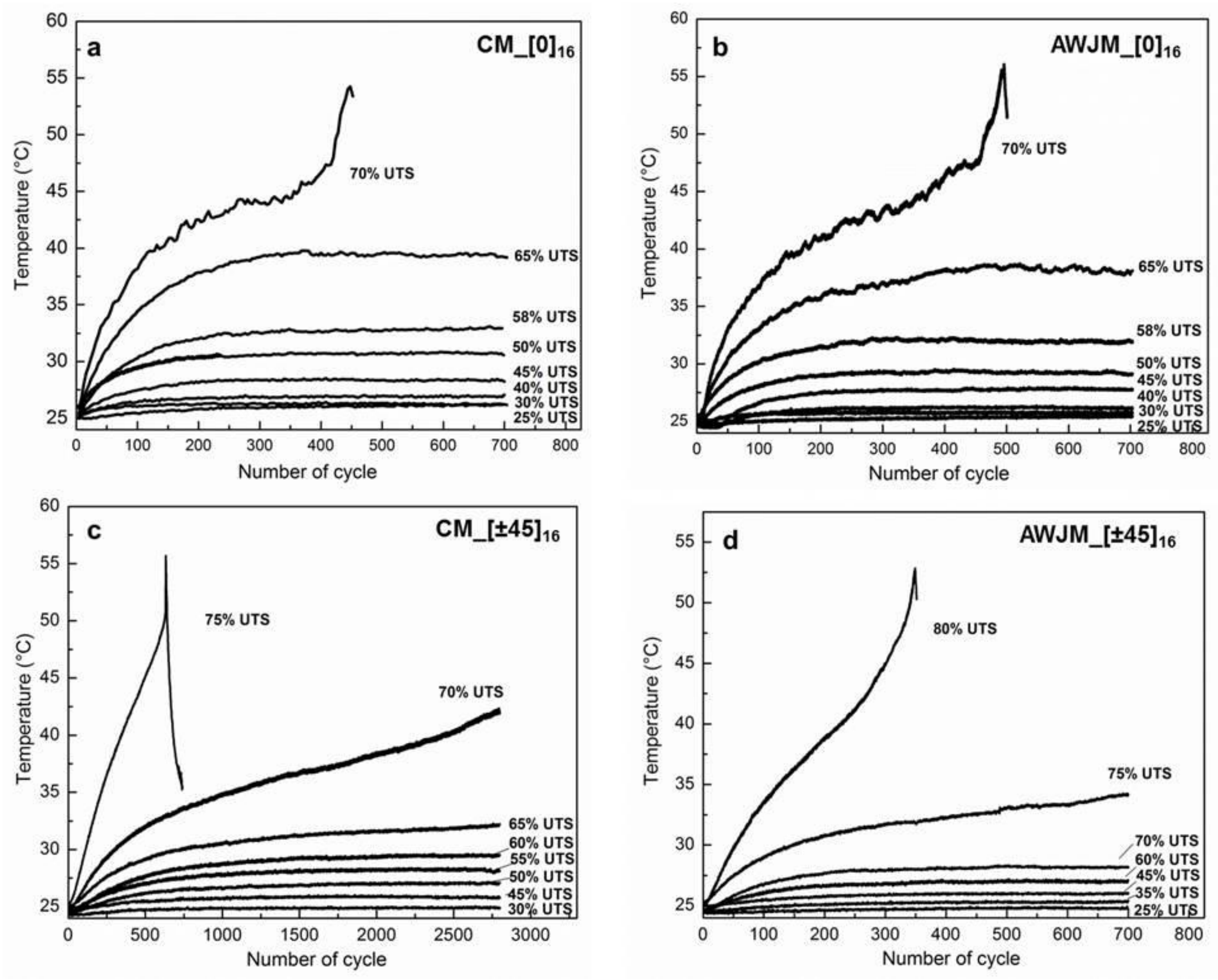


Figure 2. Thermal variation versus number of cycle for maximum applied stress (a & b) for the $[0]_{16}$ flax/epoxy laminates (c & d) for the $[\pm45]_{16}$ flax/epoxy laminates.

The failure happened at 70% of the UTS for the $[0]_{16}$ laminates machined with both machining techniques. Whereas for the laminates with $[\pm45]_{16}$ stacking sequence the failure happened at 75% of the UTS for the specimen machined with CM technique, reaching a temperature prior failure of 57°C. The failure of the specimen machined with AWJM techniques happened at 80% of the UTS after reaching a temperature of 52°C at the failure. We noticed that prior to failure of the $[0]_{16}$ laminates (i.e. plots at 70% and 65% of UTC in **Figure 2 (a)** and **(b)**) the temperature profile reached a steady temperature whereas for the $[\pm45]_{16}$ laminates the temperature kept increasing until the total failure of the composite as shown in plots at 70% of UTS in **Figure 2 (c)** and 75% of UTS in **Figure 2 (d)**. This denoted the progressive damage and failure of the $[\pm45]_{16}$ as opposed to the sudden failure of the unidirectional laminates.

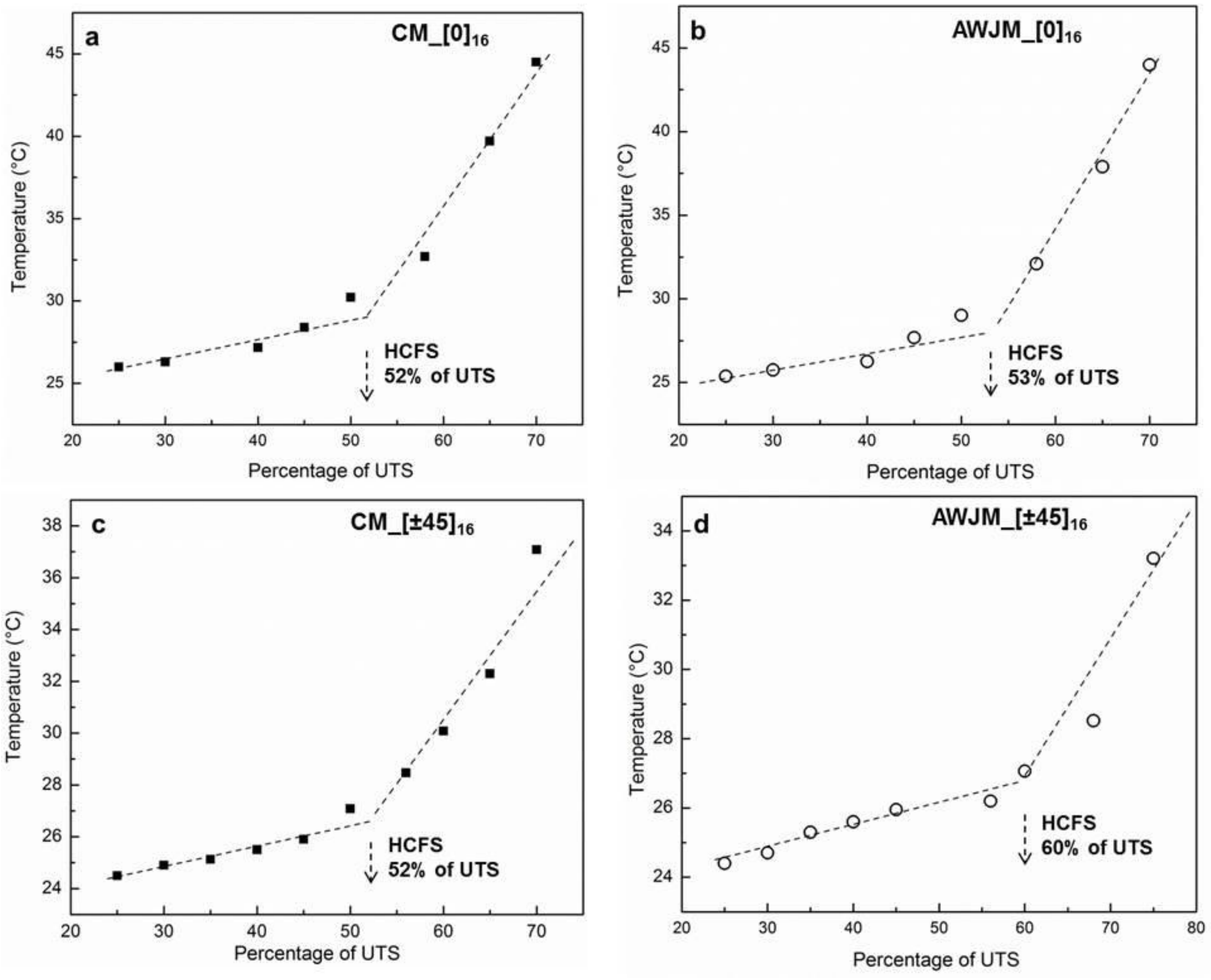


Figure 3. Average temperature increase versus the maximum applied stress (a) for the [0]16 flax/epoxy laminates (b) for the [±45]4S flax/epoxy laminates.

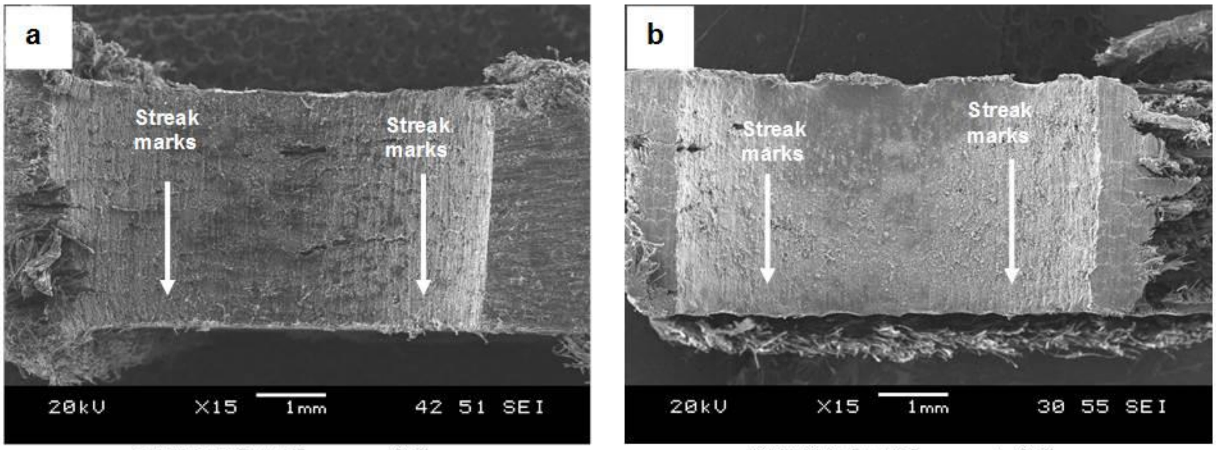
The plots of the temperature versus the applied stress level in % of UTS are presented in **Figure 3**. The bilinear nature of the data can be well seen from these graphs. We used a linear regression for each part of the plots and determined the HCFS which according to this technique corresponds to the intersection of the tow linear parts of the plot. The HCFS determined by the IR thermography method was around 52% of the UTS for the $[0]_{16}$ composite laminates. For the $[\pm45]_{16}$ laminates the determined HCFS was around 52% of UTS and 60% of UTS for the specimen machined with CM and AWJM respectively. The values of the endurance limit are summarized in **Table 1**.

Table 1. Endurance limit of different composite laminates

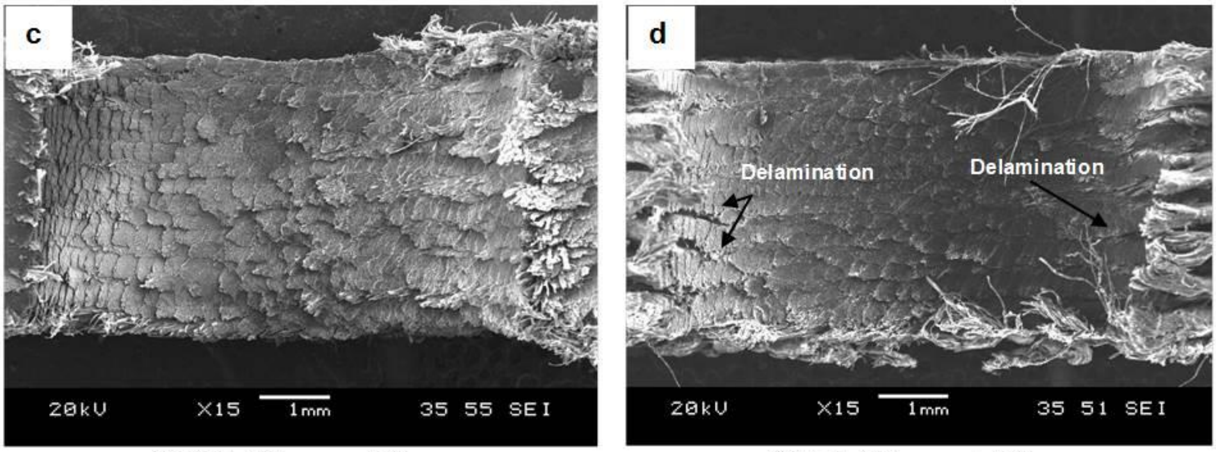
Specimen	HCFS (% of UTS)	% difference
$[0]_{16}$_CM	52	2%
$[0]_{16}$_ AWJM	53	
$[\pm45]_{16}$_CM	52	15%
$[\pm45]_{16}$_AWJM	60	

4. Fatigue Damaged Surface Analysis

SEM micrographic analysis after different fatigue failure revealed that the flax/epoxy composites undergo different failure modes depending on the machining technique and the stacking sequence of the laminate. The unidirectional $[0]_{16}$ and cross-ply $[\pm 45]_{16}$ laminates machined with water appear to have vertical streaks due to the abrasive jet. These streaks don't seem to be responsible for the failure of the specimens, see **Figure 4 (a)** and **Figure 4 (b)**. On the other hand, the laminates machined with water jet (**Figure 4 (c)** and **Figure 4 (d))** show some cracks and delamination. These damages were initiated by the material removal with the convention drilling tool that caused fiber pull-out and matrix degredation. During the cyclic loading the damges propagated in the material until the total failure and the delamination of the composite.



AWJM $[\pm 45]_{16}$ pre-failure **AWJM** $[\pm 45]_{16}$ post-failure



CM $[\pm 45]_{16}$ pre-failure **CM** $[\pm 45]_{16}$ post-failure

Figure 4. SEM images of the specimens before the fatigue tests and the fractured specimens

5. Conclusion

Infrared thermography technique was employed to analyze the heat dissipation during fatigue testing on natural fiber reinforced polymer composite plates. The results on the $[\pm45]_{16}$ laminates have shown that the damage accumulation in the specimens drilled with conventional machining process was more important than the composite plates machined with abrasive water jet technique, and the endurance limit or HCFS for the composite plates drilled with CM was inferior by 8% compared to composite specimens drilled with AWJM. This difference can be related to the initial surface integrity and the delamination that occurs on the composites induced by the difference in the mechanism of material's removal between the two processes used. On the other hand, $[0]_{16}$ Laminates which showed similar heat dissipated therefor no significant influence of the machining technique was observed for this stacking sequence.

The failure modes of the cross ply-laminated $[\pm45]_{16}$ drilled with CM can be described as fiber pull-out and delamination dominated. However, for the $[\pm45]_{16}$ drilled with AWJM no delamination was observed only flew cracks on the hole surface were noticeable. The unidirectional specimens $[0]_{16}$, showed a brittle failure for both machining techniques because of the fiber dominated characteristic of the laminate. This indicates that conventional machining technique is sensitive to the composite's stacking sequence compared to the water jet machining technique. Hence, in the presence of cross-ply (e.g. ±45 layup), the fatigue properties of the laminate may be altered when the laminate is machined with conventional machining tools.

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