Effets de la microstructure et des conditions de chargement sur les mécanismes de microfissuration au sein de composites renforcés par fibres courtes imprimés en 3D

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Effects of microstructure and loading conditions on micro-cracking mechanisms in 3D printed short fiber reinforced composites

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1. Introduction

Additive manufacturing, a layer-by-layer manufacturing process, has been involving numerous processing methods and materials since more than a decade to robotically manufacture end-use products for various industrial applications [1]. The Selective Laser Sintering (SLS) technique has been extended to new polymer powders as well as the compounding and reinforcement of neat polymers. Fiber reinforced polymer composites are being preferred for many industrial fields to improve mechanical properties of composite materials because of their high specific stiffness, strength and toughness [2, 3].

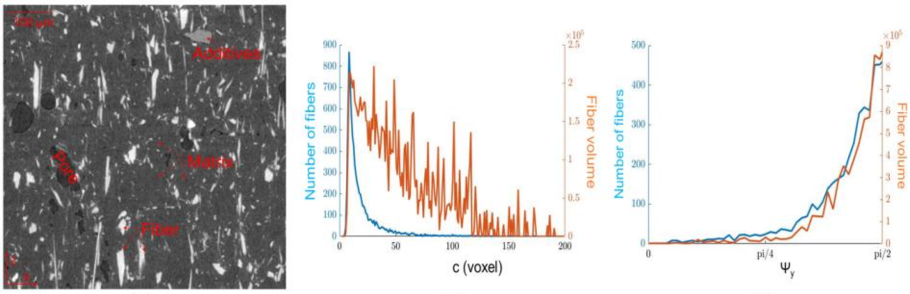
Damage mechanisms of composites, prepared via traditional methods, have been widely analyzed via optical microscopy, scanning electron microscopy and X-ray Computed tomography (XRCT) after unloading (ex-situ tests) and some in-situ tests. Additive manufacturing techniques induce some specific anisotropy on the microstructure relative to fiber and layer orientations whose effects on their mechanical behaviors are still not fully understood. The mechanical anisotropy of 3D printed fiber reinforced composites has recently been explored via ex-situ tests [4].

In the present study, XRCT observations and in-situ tests have been conducted to first characterize the microstructure of fiber reinforced composites, printed following the SLS method, and then to investigate their progressive damage micro-mechanisms. Cylindrical samples printed along various directions with a cylindrical hole in their center were submitted to uniaxial compression tests. The cylindrical hole served to induce some heterogeneous local loading conditions inducing the initiation of cracks around the hole and their stable propagation throughout the microstructure. Digital Volume Correlation (DVC) was used to measure the deformation fields and detect and characterize the crack initiation and propagation, up to the rupture of the samples.

2. Material and Test procedure

2.1 Material

The printed samples have been provided by the PRISMADD Company (Montauban). Figure 1a shows a typical cross section of an XRCT image parallel to the printing plane. The composite is mainly composed of a polymer matrix (PA12), short glass fibers, pores and additives. By extending the phase attribution method proposed by Le [5], which considers the full grey levels of all voxels to account for the partial volume effect, individual fibers can be extracted and characterized in term of fiber length, aspect ratio and orientation by calculating the eigenvalues and eigenvectors of their 2^{nd} order moment tensor. Fiber length and orientation distribution are illustrated in Figure 1b&c, respectively. It can be seen that fiber sizes cover a wide distribution, ranging between few microns and 200 µm in length. There are many small fibers (the longest dimension: c < 10 voxels = 20 µm) but their volume fraction is limited. Furthermore, fibers are preferably orthogonal to the printing direction (here Y axis), i.e. they are in plans parallel to the printing plan (XZ). Furthermore, within the printing plan, fibers exhibit a preferred orientation along Z (as shown in Figure 1a), which induces an orthotropic behavior of the printed material.



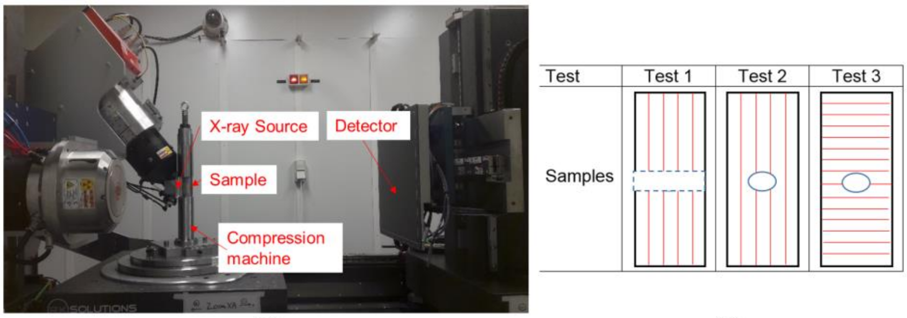
(a) (b) (c)

Fig. 1. Cross-section along printing plane (a) and fiber length (b) and orientation (c) distribution versus fiber number (blue) and fiber volume (orange).

2.2 Experimental setup and Test program

Figure 2a shows the experimental setup used for in-situ XRCT compression tests. The compression machine (maximum capacity: 20 kN) was placed on a laboratory XRCT scanner. The sample was submitted to various loading levels, with a loading rate of 0.1 mm/min, and scanned at the end of each loading step, after sample relaxation. Three cylindrical samples (diameter: 10 mm and height: 30 mm), printed along three different directions, as shown in Figure 2b, were studied.

Two types of XRCT scans were realized: the first with a voxel size of 6 µm to investigate the load distribution throughout the whole sample, and the second with a voxel size of 4 µm to focus on the crack initiation and propagation around the hole. DVC could be performed thanks to the contrast provided by the microstructure, with a correlation window of 160 µm. The resulting mesoscopic displacement fields served to remap the deformed images into the frame of the reference images so that cracks could be better observed [6].



(a) (b)

Fig. 2. Experimental setup (a) and printing layer and hole orientations in the samples (b).

3. Results

Figure 3a illustrates examples of strain fields measured by DVC around the cylindrical hole of Test 1. It can be seen that during the compression (along the sample height, Z), both zones above and below the hole were in extension (ε_{xx} was positive). Furthermore, four shear bands appeared around the hole.

With the load increase, cracks were initiated and propagated in both extension and shear zones. Figure 3b shows some cracks in the extension zone just above the hole of the sample 1. Fibers were broken.

The major damage mechanisms were cracking at fiber-matrix interfaces or fiber breaking, depending on the layer and fiber orientations in comparison with the loading direction (Figure 3 b-d). Moreover, it seems that local neighbor pores were connected during the crack propagation.

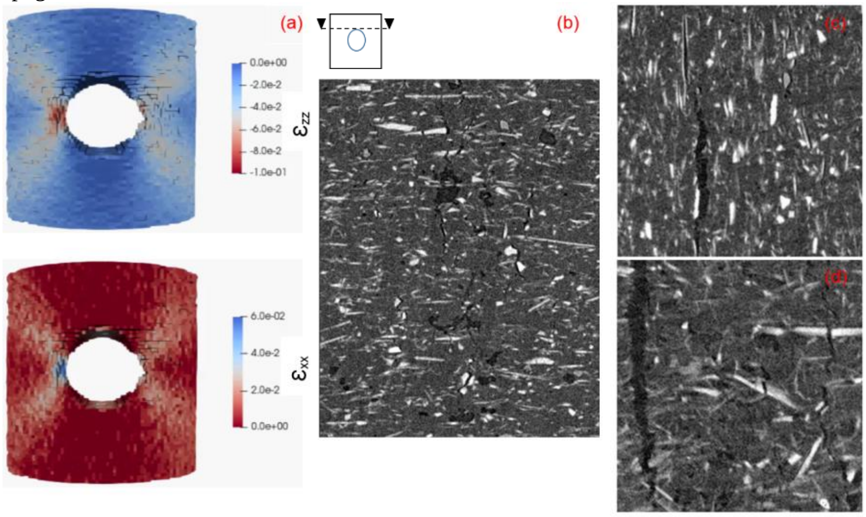


Fig. 3. : Strain fields measured by digital volume correlation (a) and cracks in extension zone of Test 1(b); Test 2 (c); Test 3 (d).

4. Conclusions

The fiber length and orientation distribution of 3D printed glass fiber composites were investigated via a new segmentation method taking into account the partial volume effect. The effects of fiber orientation as well as printing layer directions on the mechanical behaviors the composites have been investigated via in-situ XRCT in combination with digital volume correlation. Some distinct cracking mechanisms have been observed which induced strong anisotropic rupture properties of such material.

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