In Situ Study of Deformation and Fracture in a 3D Printed Short Fibre Composite

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Abstract. 3D printed structural composites can be manufactured with controlled anisotropic microstructures but contain intrinsic voids and may have inhomogeneous spatial distributions of fibres. These defects may reduce the mechanical performance, which would limit their application as structural materials. In situ X-ray tomography and digital volume correlation have been used to volumetrically characterise a polylactic acid (PLA)-basalt short fibre 3D printed composite during tensile testing to failure. The analysis distinguished the crack initiation region using the discontinuity of the displacement field, before the crack was visible. The ability to directly correlate the microstructure with crack formation may support improved control of the void distribution to design 3D printed materials with enhanced mechanical performance.

Possible Sessions

Tomography & Radiography, Testing of Additive Material

Introduction

3D printing, such as fused deposition modelling, is expected to lead a revolution of materials production into the next decade. Design of microstructure is considered one of the main advantages of 3D printing, which can be applied to short fibre composites [1]. The shear force during printing of filaments induces high fibre orientation and aligned fibres can increase the fracture resistance by deflecting the crack propagation path [2]. Although various techniques can been applied to minimise their formation, voids are intrinsic defects of 3D printing [3]. The voids and void channels that form during printing can have a negative impact on the composite's mechanical performance. The effects of fibre orientation and void distribution can be predicted using numerical simulation, but validation of such models requires non-destructive 3D characterization of deformation and damage development.

Here, we aim to investigate the initiation and propagation of damage in the anisotropic architecture of fibres and voids in a PLA-basalt 3D-printed composite. In situ X-ray tomography has applied to observe a tensile test of a multi-layer short fibre composite. The tomographs have been analysed by digital volume correlation to measure and visualise the deformation that led to material failure.

Method

The tensile sample has a cross-section of 1.05 x 4.04 mm, printed in 10 layers of 0°/45°/90°/-45°/0°/45°/90°/-45°/0° filament orientation, relative to the tensile loading direction. The X-ray tomographs were obtained with a Zeiss Versa 610 microscope, operating at 50 kV with x2 binning for a field of view of 5.49 x 5.42 mm at a voxel size of 5.44 um. Load was applied in displacement control using a Deben CT5000 tensile rig and the tomographs were reconstructed using the microscope software. Avizo 3D 2024.1® (Thermo Fisher Scientific) was used to process the reconstructed data, including watershed segmentation to detect fibres and voids and global digital volume correlation (DVC) to measure the displacement field relative to the initial stage. A coarse manual translation registration of the tomographs was carried before the DVC analysis, after which the remaining fine rigid body translation and rotations were removed using the Shoemaker method described by Mostafavi [4].

Results and Discussion

Fig.1 (a) shows a visualisation of the initial X-ray tomograph of the Basalt-PLA composite. The tomograph was segmented, based on image intensity, to quantify the fibre orientations and void distributions in 3D space. Fig. 1 (b) shows a histogram of the fibre orientation within one of the 90° layers. The fibres were well oriented, parallel to the filament direction, though some fibres were distributed less effectively. The total volume fraction of the void was 18.8% before loading, increasing to 20.5% after a nominal strain of 3% that led to stable crack formation. Most of the void fraction was connected (in blue) and located mainly between the layers due to the imperfect fusion of the filaments. Small voids are also found within the filaments.

a) b) c)

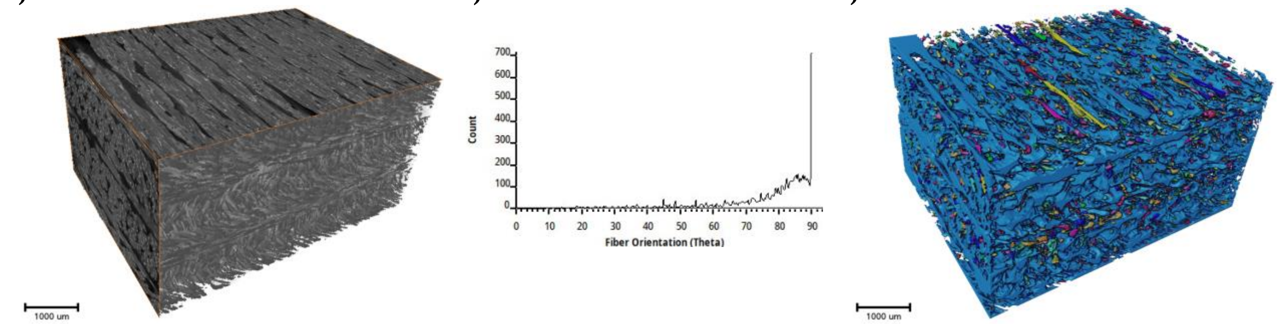

Figure 1. a) X-ray tomograph of the composite; b) histogram of fiber orientation in a 90-degree layer with 0.35° bin size; c) void distribution in 3D space. The blue voids were connected, the others were isolated.

The crack that caused the ultimate tensile failure was detected using the displacement gradient that was measured by DVC. An example line profile of the displacement U_Z at the initial stage in the loading direction (Z axis) is shown in Fig.2 (b). The crack was not yet visible - see Fig.2 (b and c), but threshold analysis of the displacement gradient can map the discontinuity onto the tomographs, as in Fig.2 (c and d). This coincides with disconnection between filaments and filament necking that developed into the visible crack after a nominal strain of 5%, as Fig.2 (d) shows. The crack propagated through interlayer-voids and caused delamination, with no significant interaction with the fibres. This shows that the interfilament voids are the dominant factor in determining the mechanical properties. Void reduction, such as via a post-printing heat treatment, might enhance the resistance to fracture.

a) b) c) d)

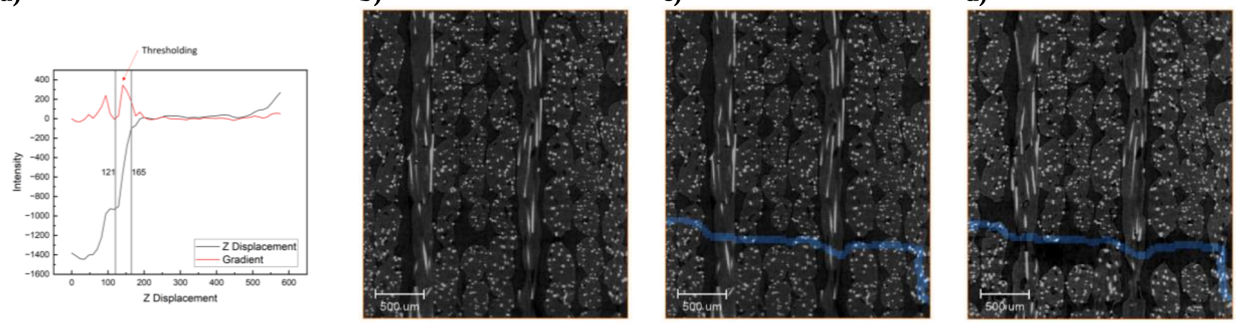

Figure 2: Damage visualization: a) the variation of displacement along Z-axis (loading direction) and the displacement gradient, after loading to a nominal strain of 3% from the initial state; b) ortho slice of the tomograph in the Y-Z plane at 3% nominal strain; c) the displacement discontinuity superposed over the same image as b) and d) then after significant damage at a nominal strain of 5%.

Conclusion

The local deformation that precedes damage imitation and cracking in a 3D printed Basalt-PLA composite can be detected using the displacement field, obtained from X-ray tomographs. Interfilament voids are the significant factor in damage initiation. A potential strengthening strategy, applied after printing, mitigate these voids.

References

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