

Significance of pore percolation to drive anisotropic effects of 3D printed polymers revealed with X-ray μ -tomography and finite element computation



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ABSTRACT

The role of porosity in 3D printed Acrylonitrile Butadiene Styrene (ABS) is studied. Dense samples are printed using fused deposition modelling with different orientations. X-ray μ -tomography is used to reveal the 3D microstructures of the printed samples. Image analysis is applied to derive porosity content, connectivity and size distribution.

Mechanical analysis is performed by converting 3D acquired images into finite element models. Simulation of uniaxial loading is carried out to predict the anisotropy induced by the printing process. Engineering constants including Poisson's coefficients and Young's moduli are derived. The results show that the low porosity content contrasts with high pore connectivity. Finite element computation reveals a slight transverse isotropy and weak sensitivity of the engineering constants with respect to sampling performed in both building and lateral directions. Comparison with experimental results indicates matching for Poisson's coefficients and higher sensitivity to printing orientation for Young's moduli. Sources of mismatching are attributed to interfacial effects where lack of inter-filament bonding is found to drive significantly filament decohesion perpendicular to the compression direction.

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1. Introduction

Fusion deposition modelling FDM is one the most versatile technique of rapid prototyping. Besides the ability of three-dimensional printing of complex parts, FDM is widely used in various applications to design dense, airy and composite materials. With regards to the increasing attention on such technique, several routes are now explored as attested by the recent review literature and the new launched thematic journals [1]. The standard processing is the laying down of the filament in the form of layers thanks to three-dimensional control of the nozzle movement. Improvement of the deposition by considering curved layer deposition is attempted by Chakraborty et al. [2]. This kind of study is motivated by the low strength usually associated to 3D printed curved objects using vertical laying down scheme. Indeed, material discontinuity occurs as a result of multiple and short filament

deposition on curved objects leading to substantial drop of mechanical performance. More flexibility of FDM is attempted by Choi et al. [3] by adapting continuously the motion of the nozzle relatively to the part to generate longer filaments, which adapt to the geometry of the part.

Another line of research focuses on the optimisation of FDM process parameters. Thrimurthulu et al. [4] opposes two major criteria for FDM, namely surface topology of the processed part and deposition duration to build optimal geometries. The authors implemented a statistical tool to derive the best geometry orientation with regards to the filament path possibilities and design criteria. In the same line of thought, topology optimisation is applied by Glantucci et al. [5] to derive optimal part geometry that satisfies thresholds in terms of material consumption, process cost and duration.

The former mentioned studies emphasis on engineering issues with less attention to fundamental understanding of the involved phenomena. From the mechanical viewpoint, anisotropy generated by 3D printing processes is a particular concern. Lee et al. [6]

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compared the anisotropy related to compressive strength of Acrylonitrile Butadiene Styrene (ABS) processed using various printing technologies. The authors demonstrated that the extent of mechanical anisotropy is imposed by the building direction. Differences in terms of yielding and ultimate properties with respect to the building direction are also achieved in the work of Cox et al. [7] of 3D printed hydroxyapatite scaffolds. The differences are explained by weak bonding between layers and structured porosity which both vary depending on the building direction. Similar anisotropic phenomena are also observed for composites manufactured using FDM. Tekinalp et al. [8] observed fibre alignment in the laying down direction in carbon fibre – ABS composites and large porosity levels induced by processing. As an attempt to reduce the anisotropy effect in 3D printed polymers, Shaffer et al. [9] considered the ionizing radiation to enhance bonding in shape memory polymers printed using FDM technology. The authors demonstrate that the large cross-link density of printed PLA induces better toughness and ultimate tensile properties thus with a lower sensitivity to the anisotropy induced by 3D printing.

It appears, from the examined literature, that the extent of anisotropy inferred to FDM is not accessible because adequate imaging tool is not used in major studies to capture 3D arrangement of microstructural heterogeneities induced by printing. In order to shed more light on the relationship between the microstructural arrangement and the elasticity performance of printed parts, this study considers the combination of 3D imaging technique and numerical approach based on finite element computation. Since porosity induced by 3D printing is dependent on the type of commercial solution, the combination of x-ray microtomography and finite element computation is able to discriminate the efficiency of printing technologies based 3D microstructural information and predicted performance. In this study, quantification of all microstructural features is achieved using X-ray μ -tomography. This 3D imaging technique is intended to analyse the microporous structure induced by processing. Images are converted into finite element model to study the relationship between the microstructure and the orthotropic behaviour of printed ABS samples. Image based finite element computation is more relevant than the CAD based finite element models. This is because differences between the CAD rendering and the real process are expected such those defects revealed through the 3D imaging technique. The relevance of image based finite element computation is illustrated by predicting the mechanical performance of full 3D printed features. In addition, scaling effects are also revealed by performing sampling inspired by clear separation between the contributions of the building direction and the transverse plane.

2. Experimental layout

The feed material is a thermoplastic synthetic polymer (Acrylonitrile butadiene styrene or ABS with chemical formulation $(C_8H_8)_x \cdot (C_4H_6)_y \cdot (C_3H_3N)_z$) purchased from CAD vision company (Guyancourt, France) under the reference P430XL ABS. This grade contains typically 70–75% of methyl methacrylate, acrylonitrile, butadiene, styrene and 25–30% of SAN (styrene acrylonitrile copolymer plastic). The glass transition of this ABS grade is 108 °C. The supplied material is provided in the form of a wire coil where the wire diameter is 3 mm. The 3D printing technology is based on fusion deposition modelling. The polymer deposition is performed in layers of 254 μ m in thickness. Cubic samples of regular dimensions (30 × 30 × 30) mm³ are printed using uPrint SE 3D printer from Stratasys. The model is built using a dual-tip technology which adjusts automatically the deposition of dissolvable support material and the printed filaments. The built-in software (CatalystEX) generates automatically the filament paths and

evaluates the possibility of including the soluble support. The printed objects are simple geometries with small overhangs. The soluble support is required only at the base level. It is removed after printing using a wave-wash cleaning system. In order to capture anisotropy effects induced by the process of filament laydown, samples are printed with different orientations with respect to the modelling base. Five orientation angles (θ) are selected from the set (0°, 30°, 45°, 60°, 90°).

Compression testing is performed on ABS blocks in three main directions X, Y and Z (Fig. 1). Experiments are conducted using a 100 kN MTS tensile/compression machine with a crosshead constant rate of extension set to 10 mm/min. Large compression stages are selected to capture the full deformed area at any load level. Large load levels are applied up to control limit of 90% of the load capacity (100 kN). This allows the clear identification of the elasticity regime and the selection of large loads below the yield point for Poisson's coefficient measurements. As a consequence, the displacement level is close to 52% of height reduction. Young's modulus is accessible from stress – strain response. Poisson's coefficient is determined from high speed camera (Phantom V7.3 from Photonline, Marly Le Roi, 78-France) measurements simultaneously conducted with compression testing (Fig. 1). Engineering constants are evaluated as function of printing orientation.

Imaging of 3D printed samples is conducted using an UltraTom X-ray μ -CT system (Fig. 2). The imaging principle illustrated in Fig. 2a shows a classical radiographic imaging setup modified by a rotating sample holder. This allows the acquisition of collection of 2D radiographic images at different angles (Fig. 2a). The 3D image is built using reconstruction algorithm that attributes a grey level value to each spatial position in the sample. This grey level value represents the local phase density inside the acquired volume. The acquisition is performed using W based filament X-rays source (Fig. 2b). The 2D radiographic images are built using a 1920 × 3536 pixels varian detector focused on a scintillating material.

A rotating table allows the acquisition of 1440 radiographic images where the Y-axis of the rotating table corresponds to the z-axis representing the layer building direction of the printed samples. The other acquisition parameters are: source energy 230 KV, voltage 60 KV, current intensity 480 μ A, spot size 30.08 μ m, Frame rate 10, number of averaging images 6, sample – source spacing 85.4 mm, sample – detector distance 361.3 mm, continuous mode acquisition.

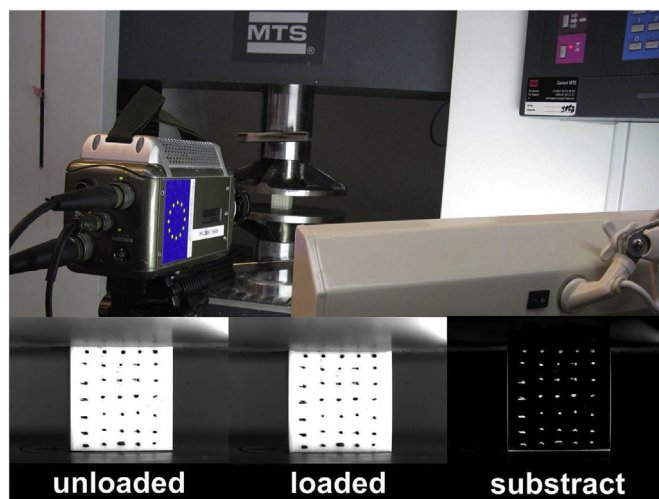


Fig. 1. Experimental set-up for measurement of elasticity constants of 3D printed ABS under compression loading conditions. Lateral displacement is extracted from image subtraction.

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