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Structural imperfections in additive manufacturing perceived from the X-ray micro-tomography perspective

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ABSTRACT

Our concern is to reveal the extent of structural imperfections of Additive Manufacturing (AM) by considering 3D imaging technique based on X-ray micro-tomography. Blocks of Acrylonitrile Butadiene Styrene (ABS) polymer are processed using Fused Deposition Modelling (FDM) with different printing orientations. Image analysis is applied to the stacks of 3D printed blocks to quantify structural attributes such as porosity content and connectivity.

The results show that pore connectivity represents the most important structural characteristic of FDM. The adopted commercial solution is able to produce acceptable porosity contents below 6% regardless of the printing orientation. Finite element results indicate the presence of expected transverse symmetry. The examination of the extent of such anisotropy is in well agreement with the observed structural imperfections mainly the porosity content. However, these predictions do not match the wide variations in mechanical performance described in the literature. The finite element analysis guides the next research step towards quantification of the imperfect bonding nature between filaments in FDM.

1. Introduction

Additive Manufacturing (AM) is presented by (Zhai et al., 2014) as the second industrial revolution of this epoch. The authors show that this term is justified by the wide impact triggered by such technology on modern society, allowing mostly anyone to be a designer.

AM is now attracting animated debates in different disciplines of research. Huang et al. (2013) point out two major concerns that need further investigation: energy and health footprints. For instance, various healthcare products can be personalised using additive manufacturing such as implants, safety equipment and other products related to tissue engineering. The same authors (Huang et al., 2013) show the positive impact of AM on energy demand with two main driving factors, namely reduction and efficiency. This impact is justified by the ability to design products of a lower energy consumption using limited amount of materials and fluids. All these aspects are expected to improve the environmental impact and product life time. Kietzmann et al. (2015) show that some of these debates are related to ethical and legal issues driven by the new role of consumer in the market. This is illustrated by the opposition between company innovation effort and consumer creativity for the design products that have certain conformity. Versatile techniques of additive manufacturing are able to shorten fabrication steps to one main between the CAD design and the real part. As shown in the review work of Pham and Gault (1998), the reduced number of manufacturing steps, for a large number of AM processes, is a vector for enhancing the competitiveness and an open gateway for optimising manufacturing cost. This comes with a certain cost as detailed in the survey by Yan and Gu (1996), which points out the limited performance, lack of accuracy and short window for material selection. All these aspects are now a major research area in AM. For instance, recent advances in electron beam melting show a large potential to control the porous structure in 3D printed cellular materials (Li et al., 2016). Such fine control of the microstructure allows the development of functionally graded materials that present advantageous biological functions such as osteoblast in bioengineering applications (Nune et al., 2016a,b, 2014).

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Research literature on the subject agrees that the primary characteristic of additive manufacturing is the ability to design complex geometries. Becker et al. (2005) show that this is a real opportunity to rethink the design without being bounded by the tooling constrain. Fused deposition modelling FDM is one the popular way of additive manufacturing. The early review on the subject by Pham and Gault (1998) categorises FDM as liquid-based additive manufacturing. Turner et al. (2014) describe FDM as a typical extrusion process, where the filament of the feed material is swiped from the support cartridge using driving wheels. The material is forced to the liquid state using a liquefier and the fused material flows from the printing tip to the modelling base. This tip is able to move relatively to the printing base in the three dimensional space. Most of the printed materials using FDM are polymers (mainly Acrylonitrile Butadiene Styrene or ABS, Polylactic acid or PLA). Recently, Carneiro et al. (2015) demonstrate the feasibility of using polypropylene as a polymer candidate in FDM starting from the filament extrusion step and ending to the small size part characterisation.

The result of lying down of the fused matter in successive layers is the development of anisotropic structuring. Ahn et al. (2002) show a strong correlation between the raster angle and the tensile properties of ABS. The authors show that tensile strength can vary in a wide range (from 2.5 to 20 MPa) depending on inter-filament crossing and orientation. Lee et al. (2007) show that failure modes under compression are distinct depending on the choice of AM technology. Shaffer et al. (2014) show that improved macromolecular crosslinking in FDM-based thermoplastic systems is achievable using gamma radiation. The authors highlight a direct consequence on increased toughness of studied polymers. These contributors (Shaffer et al., 2014) confirm that tensile responses of PLA and ABS samples are sensitive to printing orientation. The optimal response corresponds to the maximum alignment of filament in the loading direction. In addition, the results of the same authors indicate higher sensitivity of ABS compared to PLA to mechanical anisotropy. The literature work is constantly exhibiting attempts to reduce anisotropy issues by, for example, optimising the part orientation or applying post-processing to improve cross-linking. Carneiro et al. (2015) show that, besides the part orientation prevailing effect, the infill degree has also a strong effect on tensile properties of PP and PP based composites. Thrimurthulu et al. (2004) suggest the use of optimisation strategy based on genetic algorithm to achieve optimal deposition orientation with reduced stair-case effect and minimum support material. Strategies also are applied to reduce discontinuities by considering more continuous modes of printing. Chakraborty et al. (2008) argue on the benefits of using curved layer FDM to improve the processing of curved structures such as thin shell-type parts. The authors show that the reduction of the stair-case effect and smooth finishing surface state are important outcomes of the proposed FDM strategy. Choi et al. (2011) present a modified commercial set-up with capabilities of vertical layering. The authors claim that this modified set-up allows more flexibility by reducing the dependence to the building direction. For a large number of these contributions, the optimal design in AM is conducted from an engineering viewpoint, by focusing on process parameter driven effects. For instance, Galantucci et al. (2008) focus on optimising manufacturing time and cost with respect to shape factors such as the internal angle, raster and shell width. In a review paper, Mohamed et al. (2015) show that the FDM optimisation relies on building orientation, layer thickness and tool path parameters. The authors refer to the literature work to relate these influential parameters to surface roughness, part deposition imprecision, building time, and part performance.

Better actions towards the optimal design can be driven by more fundamental understanding of the nature and extent of the defects induced by AM. Thanks to the recent advances in 3D image techniques, it is now possible to achieve a clear picture of the texture and defect extent at the microstructure scale (Baker et al., 2012; Maire and Withers, 2014; Mizutani and Suzuki, 2012). This is illustrated in the work of Mostefai et al. (2015), which suggests the use of X-ray micro-tomography to achieve microstructural arrangement in heterogeneous cementiteous composite. This picture can be even more accurate if an anticipation of the microstructural performance is included through computational analysis (Moreno-Atanasio et al., 2010). This is conducted in the work of Ayadi et al. (2015), where the authors are able to combine finite element analysis and X-ray micro-tomography imaging to predict the elasticity behaviour of polymeric composites. These two types of analysis, namely X-ray micro-tomography and finite element computation are brought together in this research contribution to gain more fundamental knowledge about the process-induced defects.

Indeed, X-ray micro-tomography is used, in this study, to quantify the defects in the three-dimensional space. Part of the analysis is the determination of the porous structure and related attributes. The 3D images are converted into finite element model to capture the effect of process-induced defects on the mechanical performance of the printed parts. This study focuses on ABS polymer blocks that are printed using a commercial FDM solution.

2. Experimental layout

The ABS polymer is delivered by CADvision company (Guyancourt, France) under the reference P430XL ABS. The additive manufacturing is based on commercial solution of fused deposition modelling manufacturing. Processing is performed using uPrint SE 3D printer from Stratasys. This printing technology is equipped with two tips of 254 μm in diameter each for the deposition of ABS and a dissolvable support. Cuboids of ABS $(30 \times 30 \times 30)\,\text{mm}^3$ are printed using different orientations with respect to the modelling base. Orientation is represented by the angle θ, where the following choices are made 0°, 30°, 45°, 60°, and 90° (Fig. 1). The Stl files of the CAD models are transformed into tool paths using built-in software (CatalystEX). Due to the simplicity of the CAD model, the software plans soluble support at the first layers to prevent strong bonding to the base.

X-ray micro-tomography characterisation of the printed samples is conducted using an UltraTom X-ray μ-CT system. The acquisition parameters are: voltage 60 KV, current intensity 480 μA, voxel size 30 μm, continuous mode acquisition, resolution of 2D radiographic Images 1920 × 3536 pixels with varian detector focused on a scintillating material, 1440 radiographic images.

We need to mention that the accuracy of 3D imaging acquisition relies on the voxel size which is eight times smaller than the printing tip diameter. Stacks representing the acquired volumes are built from the collection of radiographic images using the filtered back-projection algorithm (X-Act software from Rx-Solutions). The image acquisition and the stack assembling require less than 30 min per condition. The voxel number per stack varies is of the order of one billion.

The clear separation between the solid and air phases allows the successful application of varieties of image operators, which are coded using the programming environment of ImageJ (http://imagej.nih.gov/ij/, National Institute of Health) software from the public domain. In particular, automatic thresholding is applied to grey level stacks to achieve binary images representing air and dense phases. Flooding is applied to separate the background from the air phase. Flooding is based on the flood filling tool available in ImageJ. Since the contour of the acquired ABS block is closed, we did not use sophisticated contour detection algorithms such like wrapping developed in (Mamlouk and Guessasma, 2013) to separate accurately the background from the feature of interest. Flooding is realised on binary images starting from a background pixel. All