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Microstructural defects induced by stereolithography and related compressive behaviour of polymers

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ABSTRACT

The goal of this work is to discover the defects induced by 3D printing of porous polymeric blocks using stereolithography and any related compressive behaviour. Processing of polymeric blocks containing varied porosity contents in the range 0–60% is performed. X-ray micro-tomography is used to assess the microstructural details of the polymeric blocks. Compression testing is realized up to densification on all orthogonal faces. Mechanical characterization of the blocks shows the typical behaviour of a cellular material and limited anisotropy effect related to building direction. Defects such as trapped resin, altered support structure and unbuilt porosities are quantified. This study concludes that the design of airy structures needs to exclude any form of closed porosity to enable processing using stereolithography.

1. Introduction

Additive manufacturing (AM) refers to a set of different technologies and processes used to manufacture physical models directly from a virtual prototype designed on a CAD (Computer Aided-Design) system using layer-by-layer construction. AM technology allows the freeform fabrication of parts with intricate and complex geometries without special fixtures required in material removal processes. AM processes significantly shorten the fabrication cycle time, are cost-effective for single parts and small batches, and can build parts that are not afforded by subtractive manufacturing processes. Numerous additive manufacturing processes have been developed and received remarkable success for practical applications in aerospace, automotive, biomedical, energy and other fields (Mansour et al., 2007). Some of the most popular systems include stereolithography (SL), laser sintering (LS), fused deposition modelling (FDM) and laminated object manufacturing (LOM), which use liquid, filament/paste, powder and solid sheet material, respectively (Gibson et al., 2010).

Stereolithography is one of the most important AM technologies. It holds an advantage in manufacturing parts with different geometries and dimensions due to its flexibility. Moreover, it has superior fabrication accuracy and an increasing number of available materials have been developed. Stereolithography is based on the process of photopolymerization, in which a liquid resin is converted into a solid polymer under laser irradiation (Corbel et al., 2011). The process considers a CAD model that is virtually sliced into layers of a chosen thickness to define the different horizontal cross sections of the object. These numerical data are uploaded to the SL apparatus. Laser beam radiation focuses on the surface of the liquid and the laser beam draws the pattern according to the slicing data. The UV radiation is absorbed by the photoinitiator, which in turn initiates polymerization of a liquid monomer into a solid polymer. After a solid layer is achieved, the supporting platform containing the solid part is moved away from the surface and the next layer is cured. These steps (the movement of the platform and the curing of an individual pattern in a layer of resin) are repeated layer by layer until the three-dimensional object is completely built. The part, at this stage, is termed a "green" model. The model usually needs to be post-cured under high-intensity ultraviolet radiation to complete the curing process (Dulieu-Barton and Fulton, 2000) with the purpose of stabilizing and improving the mechanical properties of SL parts.

Although stereolithography is a working technological solution, individual processes are likely to introduce some errors or defects explained below. These flaws reduce, to some extent, SL product accuracy and mechanical performance, which in turn obstruct further SL applications in product manufacturing.

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In layered manufacturing (LM), slicing of the partial CAD model is one of the important steps. Most rapid prototyping systems triangulate a three-dimensional CAD model into an intermediate form of a Standardized Triangular Language (STL) file. This form is then sliced in a uniform layer of a given thickness. However, STL files cause the problems of dimension and surface errors resulting from the approximation of three-dimensional surfaces by triangular facets. Zha and Anand (2015) presented a Surface-based Modification Algorithm (SMA) that adaptively and locally increases the facet density of an STL model. It is an error minimization approach that modifies the STL facets locally based on chordal error, cusp height and cylindricity error for cylindrical features. The authors found that this approach significantly reduces the part error of the STL model without causing an increase in the file size. Another slicing method is direct slicing of CAD models, which has greater model accuracy and reduced file size (Jamieson and Hacker, 1995).

The physical build parameters such as hatch cure depth, layer thickness, blade gap, hatch spacing, and orientation have a huge impact on the part quality. The part quality characteristics can be divided into part geometric characteristics (dimensional accuracy, surface finish) and mechanical characteristics (tensile yield, impact strength, residual stress, fatigue behaviour and failure mode). Zhou et al. (2000) investigated five process parameters on the dimensional accuracy of the multi-feature preform. Using a design of experiment approach, the authors concluded that the best build conditions necessarily combine all considered process parameters. They also suggested laser scan time as a possible leverage to part printing accuracy. Cho et al. (2002) adopted a genetic algorithm approach to identify the optimal process parameters that allow improvement of the part build accuracy. Campanelli et al. (2007) reported a statistical analysis of the stereolithographic process to determine the optimal combination of build parameters leading to the best dimensional accuracy. Sager and Rosen (2008) applied the parameter estimation (PE) method to improve the surface finish of the parts. In the reported study, the authors optimized the exposure value at each measurement point by controlling the scan velocity to obtain a smooth surface. Chockalingam et al. (2006) investigated the effect of layer thickness on tensile behaviour of SL components. It was demonstrated there that a smaller layer thickness can enhance the tensile strength.

The build orientation is one of the most important process parameters because it directly affects the part accuracy, mechanical property, build time and cost. Cheng et al. (1995) developed a multi-objective approach to determine the optimal part building orientation considering different objectives such as part accuracy, building time and other critical factors. Zhang et al. (2015) introduced a two-step solution to solve the build orientation optimization problem of simultaneous multi-part production in the same build vat. Paul and Anand (2015) developed a voxel-based approach for the building of optimal support structures and minimizing the cylindricity and flatness errors of part features. Quintana et al. (2009) used a statistical design of experiments approach to determine the influence of specific build orientation parameters on the mechanical strength of SL fabricated parts. The authors found that distinct mechanical performance was based on the particular positioning of the design.

The previously cited literature focused on the processing itself without much attention paid to the feeding material. In fact, the photopolymer resin used in SL is a key factor determining the part quality characteristics. The resin has to satisfy several requirements such as low viscosity, stability under visible light, and small shrinkage (Hagiwara, 1999). According to the reaction mechanism type, the resin can be classified into two categories, namely radical reaction type and cation reaction type. Urethane Acrylate (UA) based resins are typical for the radical reaction type. The extent of their use in applications has been limited by the distortion induced by their high volume shrinkage during post-curing. Epoxy-based resin, used for the cation reaction type, has exceptionally low volume shrinkage and good dimensional stability. Fuh and Chew (1999) studied curing characteristics (both heat- and UV-initiated) of an acrylic-based photopolymer using Raman spectroscopy, differential scanning calorimetry and differential scanning photo-calorimetry. They found that uncured and partially cured resins trapped within the photopolymer resulted in inhomogeneity of curing in the specimens causing shrinkage and distortion. Karalekas et al. (2002) conducted an experimental investigation to determine the magnitude of the shrinkage induced residual stresses and strains in acrylic-based and epoxy-based photopolymer resin used in the fabrication of SL parts. Huang et al. (2015) developed a new approach to model and predict part shrinkage and derived an optimal shrinkage compensation plan that allows dimensional accuracy. In addition to the two former types of resins, some new hybrid resins have been developed to reinforce the material behaviour (Cho and Hong, 2004; Kumar et al., 2012). Mechanical properties of various resins have been investigated (Dulieu-Barton and Fulton, 2000; Hague et al., 2004; Mansour et al., 2007; Puebla et al., 2012).

The former studies approached SL-related engineering problems from processing and material perspectives. There is still a gap in the literature for addressing the type of defects associated with the processing of SL parts, more particularly at the microscopic scale. X-ray computed tomography (XCT) is an important and powerful tool in the analysis of the internal structure of materials. It is able to visualize and evaluate pores, inclusions, cracks or defects that occur inside and at the surface of the material. In the area of additive manufacturing, XCT is applied to detect discontinuity and porosity (Thompson et al., 2016; Ziółkowski et al., 2014), characterization of defects induced by fatigue behaviour (Siddique et al., 2015), and even strain mapping (Thompson et al., 2016). XCT is adopted, in this study, to assess the microstructural details of porous polymeric blocks designed using SL. The interest on porous structures is justified first by the main characteristic of an AM process, which is material saving by optimally adding layers of materials where needed. This interest is then augmented by the fact that porous structures are good examples of complex discontinuities that SL processes need to challenge. In such a way, there is perfect matching between defect analysis and process capabilities of SL. From a technological viewpoint, as a third justification, porous structures are designed for different purposes such as weight saving, sound and heat insulation, energy and vibration absorption, acoustical control and tissue regeneration. In this study, porous structures with different pore contents are built using SL. The compressive performance of these structures is discussed and its relationship with the microstructural defects is further analysed.

2. Experimental layout

Virtual airy blocks were created using a sequential addition algorithm allowing the positioning of spherical overlapping spheres of the same diameter (8.4 mm). The number of spherical voids provided the necessary leverage to control the porosity content embedded in blocks of $30 \times 30 \times 30\ mm^3$. Seven levels of porosity contents were considered from 0 up to 60% with a step of 10%. Even if the positioning of voids was random, configurations that create material discontinuities were rejected, and the looping through the generation continued until a fully connected solid phase was achieved for the prescribed porosity content. The designed airy polymeric blocks were fabricated using a laser rapid prototyping machine. First, the CAD models of designed structures were converted into STL format files (Fig. 1).

These STL files listed the coordinates of triangles, which together constituted the surfaces of the designed structures. Second, support was generated automatically using the RpData software (Hengtong Ltd, China). Then, the designed structures were virtually sliced into 0.1 mm thick layers for the layer-by-layer fabrication process (Fig. 1). The processing was based on a liquid resin (SPR6000 epoxy from Hengtong Ltd, China) assisted by UV solid state laser systems operating at a wavelength of 355 nm and laser beam diameter of 0.15 mm. This diameter