INVESTIGATION ON MANUFACTURABILITY, REPEATABILITY, AND MECHANICAL PROPERTIES OF LIGHTWEIGHT POLYLACTIC ACID BCC-Z CELLULAR LATTICE STRUCTURES FABRICATED BY FUSED DEPOSITION MODELING

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ABSTRACT: Cellular lattice structures are of high interest, due to their high strength in combination with low weight, and can be used in various industries such as aerospace and automotive. Besides, if a biocompatible material is utilized, these cellular structures can be employed for load bearing applications in tissue engineering. Accordingly, assessing their manufacturability, repeatability and mechanical properties are very important. In this paper, these issues are investigated for Polylactic Acid as a biocompatible and biodegradable material. A cellular lattice structure with more than 90% porosity is fabricated by fused deposition modeling (FDM) process. To do so, some benchmarks are designed and fabricated to find suitable manufacturing processing parameters as well as the structure dimensions. A number of fabricated cellular lattices are then tested in compression to obtain the force-displacement curves. These curves are very similar to each other with a good resolution indicating the repeatability of the mechanical properties of the manufactured structures. The elastic modulus of the built structure and its load-carrying capacity are found to be about 43 MPa and 150 kg respectively whereas its weight is about 5.2 gr. Accordingly, this paper suggests a method to fabricate strong and lightweight cellular lattice structures with a laboratory low cost FDM machine.

1. INTRODUCTION

Cellular lattice structures (CLS) have been receiving considerable attention for few decades due to their significant benefits over dense materials including high strength accompanied by relatively low mass, and highly porous internal structure [Gumruk *et al.*, 2013]. CLS are extensively used in various engineering and medical application areas such as energy absorbers, packaging, automotive parts, scaffold in tissue engineering , heat exchanger, heat transfer, sound and thermal insulation [Kooistra *et al.*, 2007; Wadley *et al.*, 2007; Babaee *et al.*, 2012; Yan *et al.*, 2012; Gumruk *et al.*, 2013].

Nowadays, additive manufacturing (AM) processes allows to obtain innovative parts with complex geometries directly from three-dimensional computer aided design (3D CAD) models [Sun *et al.*, 1996; Yan *et al.*, 2012; Cerardi *et al.*, 2013]. In addition, , these techniques can be used to fabricate prototypes as well as end-use parts having acceptable mechanical properties and geometrical details [Yan *et al.*, 2012; Cerardi *et al.*, 2013]. Consequently AM processes have been applied to fabricate lightweight and strong porous structures which are of interest in several industries [Murat tekin, 2009; Cerardi *et al.*, 2013].

Kooistra *et al.* [2004] fabricated lattice structures using perforated aluminum alloy sheets and carried out some experimental compression tests. A number of Ti6AL4V scaffolds were fabricated through selective laser melting (SLM) and characterized mechanically and geometrically to investigate their repeatability [Bael *et al.*, 2006]. Kooistra *et al.* [2007] introduced a new method to use sheet material in making lattice structures efficiently. Wadley and Queheillalt [Wadley *et al.*, 2007] investigated hollow truss structures to improve the mechanical strength as well as the efficiency of heat transfer capability. To assess the influence of processing parameters on the mechanical properties of lattice structures, Tsopanos et al. [Tsopanos *et al.*, 2010] fabricated BCC micro-lattice structures using SLM and reported the stress- strain curve of the micro struts. These curves were calibrated using finite element simulations. Three different cellular core types, fabricated in the University of Liverpool, were investigated by Labeas and Sunaric [Labeas *et al.*, 2010]. A methodology was also developed to predict mechanical properties and deformation behavior of the structure using finite element method. The obtained results were compared with experimental measurements [Tsopanos *et al.*, 2010]. The influence of unit cell size on the possibility of manufacturing and mechanical properties of lattice structures fabricated by SLM were investigated by Yan et al. [Yan *et al.*, 2012]. Ceradi *et al.* [2013] derived a correlation between yield strength and relative density of parts fabricated by selective laser sintering (SLS) process. Gumruk and Mines [2013] investigated mechanical properties of stainless steel lattice structures fabricated by SLM process.

The catastrophic failure of space shuttle Columbia on February 1, 2003, shows that the manufacturability of cellular materials is very important [Altenbach *et al.*, 2010]. One of the most important issues, which can affect the manufacturability, is the complex internal structure of lattice structures. Such complexity may cause the need of support structures to prevent overhanging and deformation. Removing these temporary structures are very difficult and time-consuming [Yan *et al.*, 2012]. Accordingly, it is very important to investigate limitations of the process before designing and fabricating parts [Santorinaios *et al.*, 2006].

In this study, the manufacturability and repeatability of a biocompatible and biodegradable material, Polylactic Acid, BCC-Z cellular lattice structures fabricated by fused deposition modeling (FDM), an extrusion-based AM processes, are investigated. Initially, some benchmarks are designed to obtain the minimum value of strut diameter, diagonal struts angles and fabrication speed. Based on the findings of benchmark studies, a number of BCC-Z CLS's are then fabricated and tested in mechanical compression to assess their repeatability. The results show that these specimens have almost the same stress-strain curves.

The fabricated CLS is capable of carrying about 150 kg compressive load at its ultimate point while its weight is about 5.2 gr. So, this paper presents a lightweight structure with a high load-to-weight ratio which can be manufactured with a low cost process. Such a lattice structure can be used in sandwich panels for aerospace and automotive industries.

2. MATERIALS AND METHODS

2.1. Specimen Design and Fabrication

To evaluate the manufacturability of FDM for fabrication of Polylactic Acid CLS, first a BCC-Z lattice structure is modeled. This structure is used to have a good performance due to vertical struts which enable the structure to carry higher loads [Smith et al., 2013]. The structure is generated through ABAQUS 6.11-1 software using a set of vertexes and connections among which (

Figure 1). It should be noted that, in this model, no diameter has been assigned to the struts and the appropriate diameter will be found in the following steps.

Generally a BCC-Z CLS is defined by the strut distances, angle of diagonal struts, diameter of the struts, and the whole structure height. Its manufacturability, however, depends on the strut distances, diameter of the struts, and angle of diagonal struts.

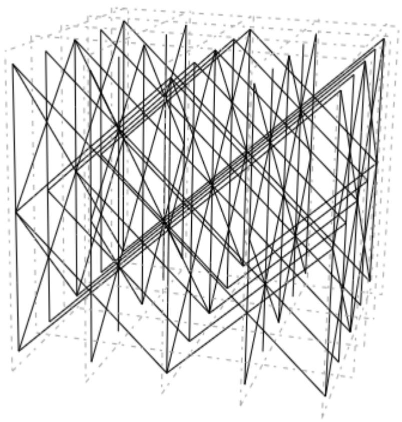

Figure 1: The lattice cellular structure designed in ABAQUS.

RAPMAN 3.2 FDM machine, a low-cost laboratory desktop AM apparatus, with 5 mm Polylactic Acid polymer filament is used to fabricate the CLS. The processing parameters used in this study are as follows: the layer thickness is 0.125 millimeter; the maximum extrusion temperature for material is 195^{o}C, and the laboratory temperature is about 25 ^{o}C.
Considering the model presented in Figure 1, three types of benchmarks are designed and fabricated with FDM. The first benchmark is designed to obtain a suitable diameter for vertical struts. It contains six columns of struts whose diameters are 1.5, 2, 2.5, and 3 millimeters (Figure 2 (a)). The second benchmark is designed to find the achievable strut diameter and corresponding angle for diagonal struts. Four columns of struts with the angles of 35, 40, 45, and 50 degrees respect to the horizontal axis were fabricated (Figure 2 (b)) for each strut diameter obtained using the first benchmark. Accordingly, proper angle and diameter are determined using these two benchmarks.

The fast movement of the machine nozzle may cause severe vibration leading to difficulties during the fabrication. Another benchmark is designed to find suitable parameters in which the effects of vibration are negligible. This benchmark has two unit cells with the obtained dimensions as illustrated in Figure 2 (c).

A plate is designed under the benchmarks as well as the CLS to repel the poor base attachment of the struts and the raft (Two layers fabricated by FDM under the part that allows the operator to separate it from the base plate of the machine). Although fabrication of less inclined struts is easier, fabrication time increases by increasing in the total height of the structure. Since the FDM machine is designed for laboratorial purposes, it is necessary to consider the overall built time of the test parts. As result, it is preferable to design the diagonal struts with the minimum possible angle, because the higher strut's angle causes higher structure's height.

Figure 3 shows the final version of the structure with the finalized dimensions obtained based on the benchmarks outputs. The final STL file is generated through Autodesk Inventor Professional 2012 commercial software. This file is then used as the input file of AXON 2.0 for generating the G-CODE to be used by the FDM machine.

(a) (b) (c)

Figure 2: Three designed benchmarks to obtain a) the minimum diameter, b) the minimum angle of struts, and c) the processing parameters

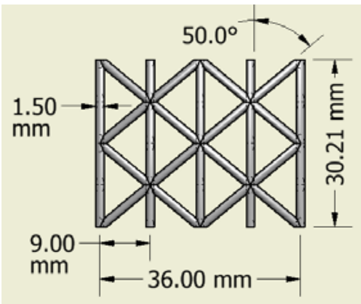

Figure 3: The dimensions of the final version of the cellular lattice structure

Three specimens with the dimensions of 36*36*30.21 mm^3 are built on the base plate and then are cut off from the base plate using a removal tool.
Figure 4 depicts one of the final fabricated CLS's.

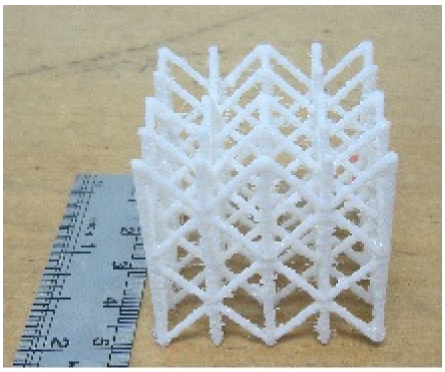

Figure 4: Cellular lattice structures fabricated by the FDM.

2.2. Mechanical Characterization
The capacity of carrying the mechanical compression loads is the most promising characteristics of the cellular structures. So, the compression tests are carried out to obtain the stress- strain curves of the CLS's. The measurements are carried out on a tension and compression test machine (SANTAM, STM-50). The first CLS is tested with the strain rate of about 10^{-4} (S^{-1}). But the deformation is localized near the moving platen indicating that the loading on the structure is dynamic. So, the velocity of the upper platen should be decreased. For other specimens the strain rate has been reduced to 10^{-5} (S^{-1}) and a more uniform deformation in the struts of the structure is observed meaning that the loading is quasi-static. The compression tests are carried out using this value of strain rate for all specimens, and the average stress-strain curve is reported.

3. RESULTS AND DISCUSSION

3.1. Mechanical Properties
The CLS specimens are compressed at $\dot{\varepsilon} = 10^{-5}\, 1/s$. The force- displacement of the structure (not presented here) shows the load carrying capacity of the structure is about 150 kg, which is impressive compared to the weight of the fabricated CLS that is about 5.2 gr.
Figure 5 shows the stress- strain curve of the CLS. The stress is calculated by dividing the applied force to the area parallel to the loading direction, and the strain is calculated by dividing the deformation of the CLS in the loading direction by the CLS's height.

As the obtained curves are nonlinear even in small strains, the method presented in ASTM D695 which is suitable for elastomeric foams with high nonlinear stress- strain curves is used [Kinney *et al.*, 2001]. In this method, a piecewise polynomial is fitted to the stress-strain curves. Then the maximum value of the derivative of the polynomial is assumed to be the Young's modulus. Using the above-mentioned method, the elastic modulus is calculated to be about E_{CLS}=43.07±0.13 MPa.

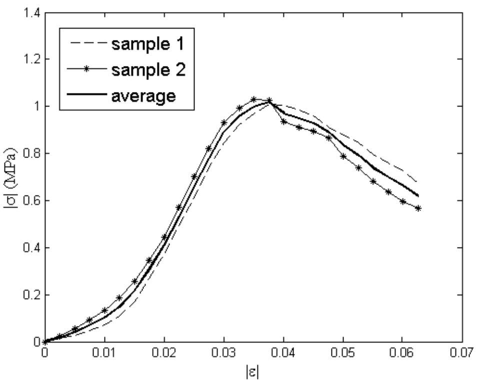

Figure 5: Stress- strain curve of the CLS

3.2. Porosity Measurement

The CLS porosity is measured using the Archimedes' principle [Yan *et al.*, 2012]. In this paper, one specimen is used to measure the porosity. This specimen is tested three times and the average value of the porosity is obtained to be about 90% while the CAD model predecits the amount of 92.68%.

4. CONCLUSIONS

In this study, the manufacturability and repeatability of polyamide BCC-Z CLS's fabricated by FDM is investigated. To do so, some benchmarks are designed to obtain the suitable value of strut diameter, diagonal struts angles and fabrication speed. Three BCC-Z CLS's are fabricated using the reults of the benchmarks. The mechanical comperession test is performed on CLS's and the stress- strain curves are obtained. The results show that these specimens have almost the same stress- strain curves which illustrate the repeatability of the fabrication process. Furtherore, the elastic modulas is calculated using the method presented for elastomeric foams to be about 43.07 MPa.

The force- displacement curve shows the fabricated CLS is capable of carrying about 150 kg while its weight is about 5gr as well. So, this paper suggests a method to fabricate strong and lightweight cellular lattice structures with a laboratory low cost FDM machine.

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