Mechanical properties and failure mechanisms of 3D-printed PLA scaffolds: A preliminary study

B I Mitrin¹, S V Chapek²*, E V Sadyrin¹ and M V Swain¹,³

¹ Research and Education Center “Materials”, Don State Technical University, Rostov-on-Don, Russia
² Joint Research Laboratory “Engineering Technologies in Medicine”, Don State Technical University, Rostov-on-Don, Russia
³ Department of Aerospace, Mechanical and Mechatronic Engineering, University of Sydney, Sydney, Australia

*e-mail: s.chapek@sci.donstu.ru

Abstract. Polylactic acid (PLA) porous composite scaffolds with three different infill patterns were subjected to compression testing. The composites were fabricated by 3D printing based on Fused Filament Fabrication (FFF) technology. Stress-strain curves were obtained which allowed to identify Young’s modulus, yield point and residual strain of samples. 3D tomography images were taken before and after deformation. Comparison between images corresponding to a particular sample were used to identify deformation and failure mechanisms.

1. Introduction
Polymer composites are widely used for biomedical implants and scaffolds for bone replacement prostheses [1]. The widespread utilization and uptake of these materials is made possible by rapid advances and development of common methods for 3D printing of thermoplastics [2]. Such methods include selective laser sintering (SLS), fused filament fabrication (FFF), and others [3]. Polylactic acid (PLA) plastic is a common choice for 3D printing because of its availability and excellent thermoplastic properties [4]. It combines sufficient mechanical strength, good biocompatibility and biodegradability [5]. Also, PLA scaffolds are capable of surface modification using various biocompatible hydrogels to improve bio-integration processes [6].

A critical feature especially for polymer composite implants and prostheses is that they must exhibit necessary strength, depending on their load bearing applications. For example, scaffolds for bone prosthesis should be able to withstand static loading up to 3 kN [7]. Typically the mechanical strength is measured using uniaxial compression [8] or tension experiments [9]. A key feature of scaffold structures is the requirement of sufficient porosity to enable bone and vascular ingrowth but at the same time sufficient strength for their load bearing requirement.

Computed microtomography (microCT) is a modern method for non-destructive investigation of inner structure of materials, control of product shape, localisation of defects and other control and evaluation purposes. Also microCT facilitate in situ testing, allowing visualization and characterization of the deformation and damage processes within the material along with mechanical properties determination [10].
To date, several studies have been conducted on the mechanical properties of PLA scaffold composites with different geometry of interconnections [11]. However, deformation mechanisms were not analysed in detail. In this work we used microCT to study changes occurring in the structure of PLA composites as a result of a compression test. This provides the possibility for further refinement of spatial structure of biocompatible polymer composites to improve strength characteristics, reduce mass and advance their biocompatibility.

2. Materials
Poly(lactic) acid filament (PLA; REC 3D, white, filament 1.75 mm Ø) was used for scaffold fabrication. 3D printing was carried out using the Ultimaker 2+ printer (Ultimaker, USA), which relies on Fused Filament Fabrication (FFF) technology. Fusion 360 software (Autodesk, USA) was used to create solid models sized 10x10x5 mm and save in .stl file format. The printing head was controlled by a computer in three axes (x, y, z with xy velocity up to 30 mm/s) during filament extrusion using the Ultimaker CURA 4.6.1 software. The extrusion system directed the filament to a print head heated to a temperature above the PLA melting point (the nozzle temperature was 180 °C). The molten PLA was then extruded through a stainless steel nozzle with a diameter of 250 microns onto a glass printing platform heated to 60 °C. The scaffolds were 3D printed in a layer by layer manner in the rectangle shape. Three types of infill pattern were used (see figure 1): gyroid (G), cubic (subdivision) (CS), triangular (T). The appearance of the samples is shown in figure 1. The manufacturing parameters are shown in table 1. The density of these different scaffolds is also listed in table 1.

![Figure 1. 3D rendering and photo of PLA scaffold samples with different infill pattern: a) gyroid, b) cubic (subdivision), c) triangular](image)

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**Figure 1.** 3D rendering and photo of PLA scaffold samples with different infill pattern: a) gyroid, b) cubic (subdivision), c) triangular
Table 1. PLA composite samples fabrication characteristics

| Infill type | Layer height, µm | Extrusion width | Print temperature, °C | Printed mass, g | Density, g/cm³ |
|-------------|------------------|-----------------|-----------------------|----------------|---------------|
| G           | 250              | 100%            | 185                   | 0.164          | 0.328         |
| CS          | 250              | 100%            | 185                   | 0.310          | 0.620         |
| T           | 250              | 100%            | 185                   | 0.271          | 0.542         |

3. Methods

Mechanical testing was carried out using CT5000-HECSS machine (Deben, UK). Series of 3 to 5 samples was tested for each infill type. The test protocol was as follows. Compression plattens moved under displacement control with constant velocity of 5 µm/s (0.3 mm/min) and displacement was stopped at a load of 1200 N for samples CS and T and 350 N for samples G. After this, the displacement was held constant for 30 seconds before unloading at 5 µm/s (0.3 mm/min). The load profile is illustrated in figure 2. To study how spatial structure damage of samples was affected by the test, tomography procedure was carried out before and after loading. For this purpose, the test rig was conducted within a lab-based microCT Xradia Versa 520 (Carl Zeiss X-Ray Microscopy, USA). Tomography of 1 sample from each series (CS, T, G) was undertaken. Before each tomography, the loading conditions were held constant for 15 minutes.

![Figure 2](image-url)

Figure 2. Compression load-time profile for the different PLA scaffold designs: a) without microCT, b) with microCT (one sample per each scaffold design). Punctured and solid squares mark the beginning and the end of microCT acquisition, correspondingly.

MicroCT scanning was conducted using an Xradia Versa 520 unit (Carl Zeiss X-ray Microscopy, Inc., USA). The Macro lens (0.4X optical magnification) was used. The distance from the sample to X-ray source and to the detector assembly was selected to maintain voxel size 20µm and avoid appearance of the aperture in the field of view. The 2048x2048 pixels CCD camera was maintained at −59°C and the acquisition was performed with camera binning factor = 2, which resulted in up to 1024x1024 pixels sized projection images. The X-ray source parameters were as follows: 80 kV accelerating voltage, 6.5 W power. The LE3 source filter was selected based on the observed transmittance values according to the recommendations of the Xradia Versa 520 User’s Guide A003030 Rev. B. The exposure time 0.25 s was selected to maintain count (intensity) values > 5000 with the selected source parameters and filter. The Dynamic Ring Removal (DRR) option, which enables small random motions of the sample during acquisition, was enabled for all the projections. Before each tomography procedure, 5 reference (air) X-ray images were acquired. The average of these references was applied to each projection. Half-hour long warm-up scan was performed with the same source parameters before each acquisition. Total number of projections was 1001.

The obtained X-ray projections were reconstructed using XRMReconstructor 12.0.8086.19558 software (Carl Zeiss X-ray Microscopy, Inc., USA) with manually adjusted centre shift values, σ = 0.5 Gauss blurring filter and BH = 0.05 standard beam hardening correction. For drift correction, Advanced
Motion Compensation (AMC) was used. Visualization of differences between initial and deformed samples was made using VGSTUDIO MAX 3.4 software (Volume Graphics GmbH, Germany).

4. Results

4.1. Compression tests

Force-displacement curves of the tested samples are shown in figure 3 for each series of samples. All the tests displayed an initial “toe-in” response because of minor surface roughness aspects associated with initial contact upon loading. The yield point of the sample G-3 was reached at 400 N load, and this was the reason to limit the load for the subsequent samples from the G series to 350 N.

![Figure 3](image_url)

**Figure 3.** Force-compression curves of samples with different infill types: a) gyroid (G), b) cubic subdivision (CS), c) triangular (T)

For more convenient comparison of mechanical behaviour of different samples, typical force-compression curves for one sample from each series are shown in figure 4a. The associated engineering stress versus engineering strain responses are shown in figure 4b.

![Figure 4](image_url)

**Figure 4.** Comparison between typical a) force-compression b) stress-strain curves for each infill scaffold type. Dash lines correspond to linear fitting of loading portion of curves used to calculate Young’s modulus

All the samples express severe non-linear behaviour from the very start of loading which arises from the uneven nature of the loading surfaces of the scaffolds. An estimate of the Young’s modulus was obtained from the linear portion of the stress-strain response as shown in figure 4b. The yield strength and residual strain of each sample is given in table 2. Data averaged by infill type is presented in table 3.
Table 2. Measured mechanical characteristics of samples

| Series | Sample index in series | Young’s modulus, MPa | Yield strength, MPa | Residual strain |
|--------|------------------------|----------------------|--------------------|----------------|
| G      | 3                      | 73.4                 | 1.7                | 5.1%           |
|        | 4                      | 96.6                 | 0.5                | 5.0%           |
|        | 5                      | 84.6                 | 2.3                | 4.7%           |
| CS     | 2                      | 110.0                | 4.0                | 19.0%          |
|        | 3                      | 126.3                | 4.5                | 14.7%          |
|        | 4                      | 117.9                | 3.9                | 16.3%          |
|        | 5                      | 97.7                 | 3.5                | 19.2%          |
| T      | 1                      | 189.6                | 4.2                | 6.7%           |
|        | 2                      | 209.5                | 6.8                | 4.9%           |
|        | 3                      | 238.1                | 3.9                | 4.6%           |
|        | 4                      | 217.8                | 5.0                | 5.4%           |
|        | 5                      | 168.2                | 4.7                | 9.7%           |

Table 3. Measured mechanical characteristics, averaged in series

| Series | Average Young’s modulus and standard deviation, MPa | Average yield strength and standard deviation, MPa | Average residual strain and standard deviation |
|--------|-----------------------------------------------------|---------------------------------------------------|-----------------------------------------------|
| G      | 84.9 ± 11.6                                         | 1.5 ± 0.9                                         | 4.9% ± 0.2%                                  |
| CS     | 113.0 ± 12.2                                        | 4.0 ± 0.4                                         | 17.3% ± 2.2%                                 |
| T      | 204.6 ± 26.8                                        | 4.9 ± 1.1                                         | 6.3% ± 2.1%                                  |

4.2. MicroCT

Figure 5 illustrates the structure of samples subjected to compression. For each of samples, it shows a virtual cross-section uncovering its inner structure before and after loading.

For gyroid infill (samples G), one may note slipping of particular fibers as a main failure mechanism. Also, the lower quarter of the image shows more deformation than the upper part. For cubic subdivision (samples CS) and triangular (samples T) infill, it can be seen that the structure collapses more evenly, which can be considered as a benefit.

4.3. Analysis

It is well known from theory and experiments (Gibon and Ashby, 1999) [7] that, in cellular structures, effective mechanical properties (such as Young’s modulus) is predominantly influenced by relative density $\rho^*/\rho_s$, where $\rho^*$ is the cellular material density, and $\rho_s$ is the density of solid material which cells are made of. Gibson and Ashby (1999) [7] found useful theoretical expressions for relative characteristics of the cellular material depending on density and other parameters, which were confirmed by numerous experiments. For example, for the open cells foam material it holds that

$$\frac{E^*}{E_s} = C_1 \left(\frac{\rho^*}{\rho_s}\right)^2$$

where $E^*$ is the cellular material Young’s modulus, $E_s$ is that of the cell material, and $C_1$ is a constant. It was found from experiments that $C_1 \approx 1$ for most of materials.
Another interesting case is a honeycomb material. For out-of-plane loading, we have

\[ \frac{E'}{E_s} = \frac{\rho^*}{\rho_s} \]

If cells of a honeycomb are regular hexagons with walls of uniform thickness, for in-plane loading we have that

\[ \frac{E'}{E_s} \approx 2.3 \left( \frac{t}{l} \right)^3 \]

Taking into account the relation \( \frac{\rho^*}{\rho_s} = \frac{2 \cdot t}{\sqrt{3} \cdot l} \), we get the approximate formula

\[ \frac{E'}{E_s} \approx 1.5 \left( \frac{\rho^*}{\rho_s} \right)^3 \quad (2) \]

Equations (1) and (2) can give us a theoretical measure of Young’s modulus for a honeycomb or foam material made of PLA. Figure 6 shows the values of Young’s modulus versus density for the scaffolds obtained here, together with theoretical curves derived from equations (1) and (2). Here we took the parameters values \( E_s = 3.0 \) GPa and \( \rho_s = 1.3 \) g/cm\(^3\) provided by a filament manufacturer.

5. Discussion

From figures 3, 4 and tables 1, 2 one can see that samples G (a) exhibit minimal resistance to deformation. Samples CS (b) are more resistant, and samples T (c) seem to be strongest. From microCT
data we found that deformation is distributed more evenly in samples CS and T that possibly can lead to higher durability of these scaffolds under compression loads.

![Figure 6. Experimental (PLA scaffold) and theoretical (foam and honeycomb PLA material) values of Young’s modulus versus density](image)

Comparison with theoretical data on cellular structures (Figure 6) shows us that our scaffolds express lower value of elastic modulus than can be theoretically expected for a foam material made of PLA. Gyroid (G) structure seems to be more optimal in terms of elastic modulus to density ratio. It would be interesting, therefore, to test mechanical characteristics of more dense gyroid scaffolds.

Let us note that due to the lack of symmetry in the considered scaffold structures and due to the layerwise nature of 3D printing the considered sample should express anisotropy. Thus, if we decided to measure properties in the orthogonal direction, most likely they will differ from ones observed in this study.

### 6. Conclusion

Mechanical tests of biocompatible PLA composite samples were carried out. Samples were made using FFF 3D printing with different infill structures. The conducted tests allowed us to measure mechanical characteristics of samples. The highest strength was observed on samples with triangular infill (series T). Application of microCT allowed us to reveal features of deformation inside the material. The obtained results show the importance of careful choice of infill for samples aimed at biomedical applications. We suggest that, based on mechanical tests joined with microCT study, optimization of spatial structure of 3D printed material can be conducted.

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