3D Printed Thermoplastic Polymers for Bone Replacement

Azem Yahamed, Pavel Ikonomov, Michael Joyce, Paul D. Fleming and
Alexandra Pekarovicova

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Abstract

Several thermoplastic polymers were 3D printed using Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and PolyJet™ Technology. The samples were printed with specifically designed thicknesses that ranged from 400 µm for the thickest sample down to 16 µm for the thinnest one. There was found great consistency between the thickness and roughness of the printed samples. From the obtained results, the samples produced by the Stratasys 500 Objet Connex3 are smoother than MakerBot replicator 2X and FlashForge Creator Pro, which use FDM technique. It was found that different 3D printing produce different smoothness of the layer at a desired layer thickness. Smoothness of 3D printed layers was monitored using white light interferometry employing a Bruker (Contour GT-K) instrument. Out of all tested devices, the Stratasys Objet 500 Connex3 produced the smoothest 3D printed layers, which is crucial in the human bone replacement field. It was also found that the samples printed at 90° were smoother than those printed at 45°, which shows that the print orientation had a significant influence on roughness of the printed layer, but little on its thickness. Solid assemblies as well as structures with internal engineered structure were designed and printed. SolidWorks software was employed to design the internal engineered honeycomb structures with different geometric shapes (hexagonal, triangular, and square) with voids of about 400 microns. Tensile energy of solid and honeycomb structures per unit mass was measured and calculated (tensile strength/density), and it shows that the square PA2200 void structure has almost identical tensile strength as PA 2200 solid structure. The void geometry of the honeycomb structures reduces the amount of material, thus minimizes the weight, cost and construct density of 3D printed features.

Western Michigan University

Introduction

The study of biomaterials for bone replacement has progressed significantly over many years [Stevanovic, 2013]. There are many examples of applications of 3D printing in creating implantable organs that are designed for specific patients to enhance accuracy and efficiency of manufacturing. 3D printing uses computer models to build three-dimensional objects by printing layers of materials, including plastics, metals, powders and liquids layer by layer. The process is also used to build items in the medical field that meet the exact requirements and dimensions of specific patients [Kern, 2015]. Several processes can be more successfully accomplished with use of a 3D printing technologies [Miller, 2016]. Three-dimensional printing can improve medical care in some cases, and it may also open new opportunities for bone replacement or cure. The technology has been used in the field of prosthetics and drug printing. 3D models are produced through constructive processes. It is very likely that more medical professionals will introduce 3D printing technologies into their practices. 3D printing gives enormous benefits for experts to produce only what they need, which can reduce production time. It allows objects from actual human scans to be modelled and built for further application in a few hours, even inside medical facilities. Making 3D models by using inkjet technology can save time and cost because designing, printing and assembling disconnected parts of the model is not needed. 3D printing technology can make models of objects either designed with a CAD program or scanned with a 3D scanner. The technology is used widely in many applications as industrial design, engineering, architecture, construction, aerospace, automotive, dental and medical applications. 3D printing technologies allow precision manufacturing of bone structures for replacement of the missing/broken parts created from actual Magnetic Resonance Imaging (MRI) or Computed Tomography (CT) scan DICOM images. The possible technologies for 3D printing are illustrated at the Figure 1[Guvendiren, 2016].

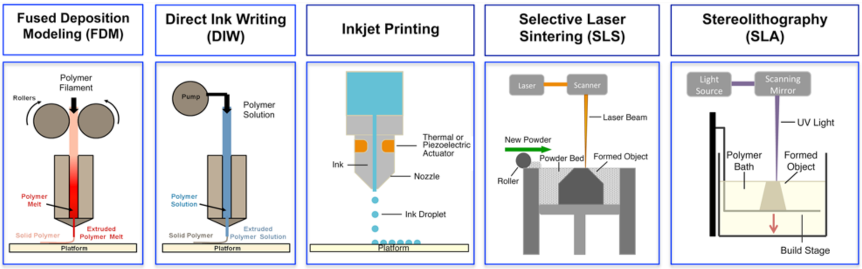

Figure 1: *Different technologies of 3D printing [Guvendiren, 2016]*

The aim of current study was to analyze thickness and roughness of 3D printed layers in relationship with print direction and print device used, to compare printed features by various 3D print devices and polymers, and to test the mechanical properties of 3D solid and honeycomb structures printed by various thermoplastic polymers.

Experimental

Fused Deposition Modeling (FDM) was used to print Acrylate Butadiene Styrene (ABS), Polylactic Acid (PLA) and ULTEM 9085 (polyetherimide). For FDM printing, printers Stratasys Fortus 400 MC, MakerBot Replicator, Flash Forge Creator were employed. Selective Laser Sintering (SLS) was used to print PA2200 (Polyamide) on EOSP 396 printer. Stratasys Objet 500 Connex3 printer (PolyJet Technology) printed Digital ABS. The trabecular (spongy) bone structure with the average pore size of ~400 µm of three different geometries, hexagonal, triangular and square, were designed (Figure 2) and printed along with solid structures. The test samples were designed according to the industry standards with specific dimensions. ISO 3167 standard was employed for tensile strength test. An MTS Bionix Servohydraulic Test Systems-Model 370.02 was used for testing. Thickness and roughness of printed layers were measured using a White Light Interferometer (Bruker Contour GT-K).

Results and Discussion

Solid assemblies as well as structures with internal engineered structure were designed and printed. SolidWorks software was employed to design the internal engineered honeycomb structures with different geometric shapes (hexagonal, triangular, and square). The samples were printed using different 3D printing methods [Yahamed, 2016]. The aim was to create structures with similar mechanical properties as found in human trabecular bones. Structures with the average pore size of the real trabecular bones (400 µm) were designed. The designed structures are shown at Figure 2. We calculated the void volume and percentage of infill for designed structures with different geometric shapes. Table 1 shows the void volume fraction, fill fraction and percentage of infill for the geometric shapes. We wanted to investigate the influence of the geometric shape on the percentage of infill and the impact of the percentage of infill on the strength. Table 1 shows that the hexagonal structure has the highest percentage of infill 92.6%, followed by the triangular structure 83.6% and the lowest is the square structure 82.9%. Figure 2 exhibits tensile energy of solid and honeycomb structures per unit mass (tensile strength divided by density), which shows that the square PA2200 void structure has almost identical tensile strength as PA 2200 solid structure. The void geometry of the honeycomb structures reduces the amount of material, thus minimizes the weight, cost and construct density of 3D printed features.

Solvent	Surface Tension [mN/m]	Evaporation Rate
Ethylene glycol	47,3	0,01
1-butanol	26,2	0,46
1-methyoxy-2-propanol	27,7	0,71

Table 1: *Void volume fraction and percentage of infill for designed structures*

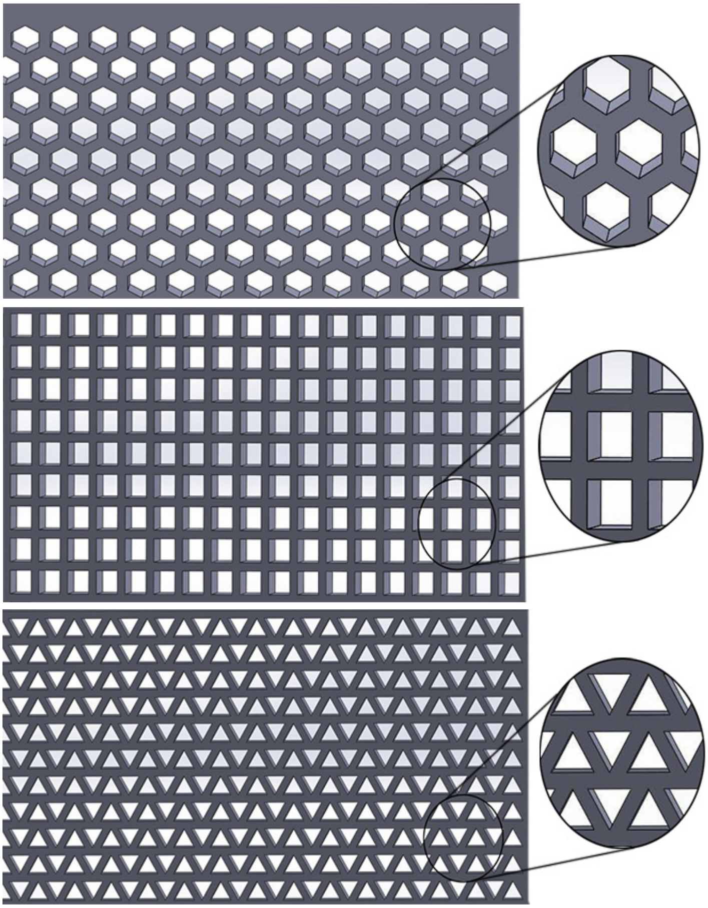

Figure 2: *Hexagonal (Top), square (Middle) and triangular (Bottom) architecture*

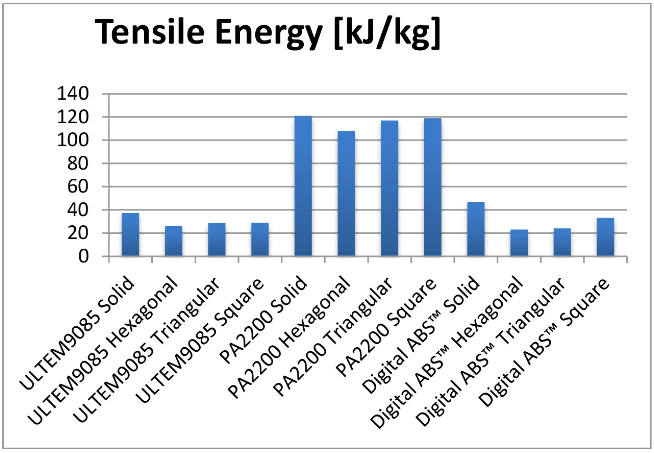

Figure 3: *Tensile energy per unit mass of solid and honeycomb structures*

The solid samples were also printed with specifically designed thicknesses that ranged from 400 µm for the thickest sample down to 16 µm for the thinnest one (Figure 4 and 5). There was found great consistency between the thickness and roughness of the printed samples. Results show that the samples produced by Stratasys 500 Objet Connex3 are smoother than MakerBot replicator 2X and FlashForge Creator Pro that use FDM technique. It was found that different 3D printing produce different smoothness of the layer at desired layer thickness. Smoothness and roughness of 3D printed layers was monitored using white light interferometry employing Bruker (Contour GT-K) instrument (Figure 7). Out of all tested devices, Stratasys Objet 500 Connex3 [Stratasys, 2016] produced the smoothest 3D printed layers, which is desirable in the human bone replacement field. It was also found that the samples printed at 90° (Figure 6) were smoother than those printed at 45°, which shows that the print orientation had a significant influence on roughness of the printed layer, but little on its thickness. Out of all printers employed, Stratasys 500 Objet Connex3 was most accurate or precise of all tested 3D printers, and was found to produce the thinnest layers.

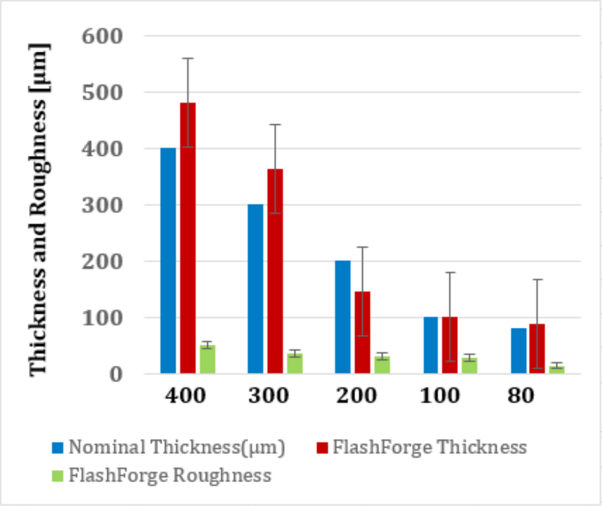

Figure 4: *ABS thickness and roughness for layers printed at 45° with FlashForge Creator Pro*

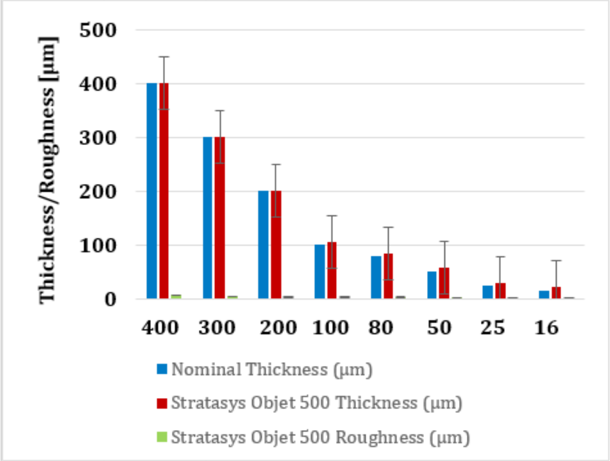

Figure 5: *Digital ABS™ thickness and roughness for layers printed at 45° using Stratasys 500 Objet Connex3*

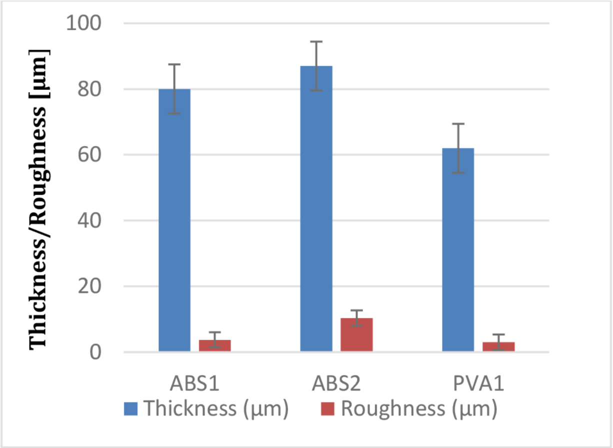

Figure 6: *Thickness and Roughness for ABS (1 or 2 layers) and PVA layers printed at 90°*

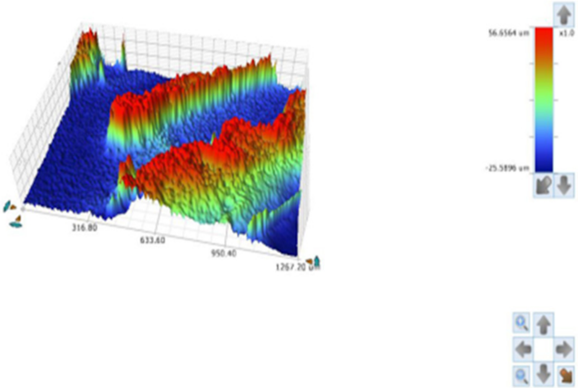

Figure 7: *Topography of second layer of ABS by white light interferometry*

Conclusions

The samples printed at 90° were smoother than 45°, which means print head orientation had a significant influence on roughness. The thickness of the printed samples using MakerBot better match the designed thickness than ones produced by FlashForge. Stratasys 500 Objet Connex3 using Polyjet technology printed smoother samples than MakerBot and FlashForge. Stratasys 500 Objet Connex3 printed more precisely and reached thinner layers than other printers.

The voided geometry of the honeycomb structures reduces the amount of material, thus minimizes the weight, cost and construct density.

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